Parallel-Processing Astrophysical Image-Analysis Tools

Kenneth Mighell

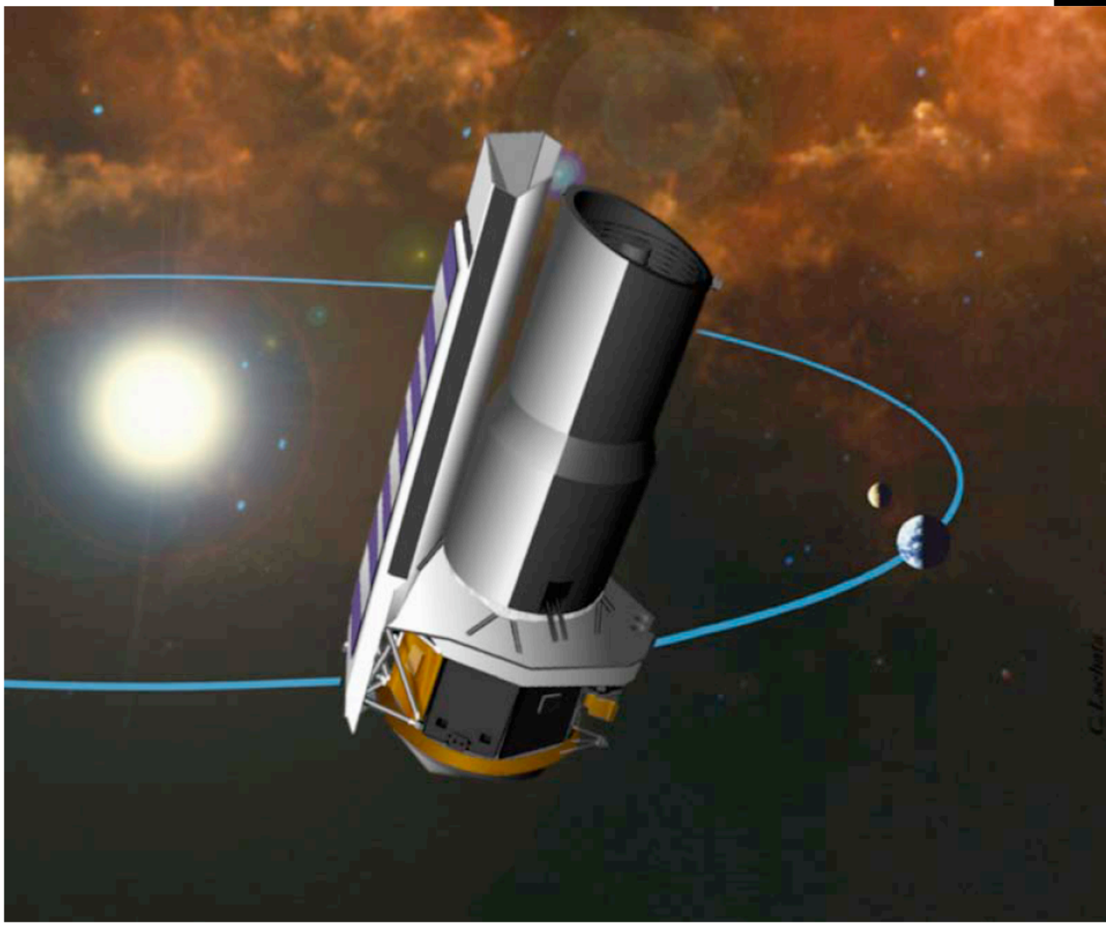
National Optical Astronomy Observatory

NASA *Applied Information Systems Research Program* Principal Investigators Meeting
University of Maryland, Inn and Conference Center May 5–7, 2008

Outline

- *Spitzer Space Telescope's* Infrared Array Camera
- **CRBLASTER** : A Fast Parallel-Processing Program for Cosmic-Ray Rejection
- NMP ST-8 Dependable Multiprocessor TRL-6 Validation Effort

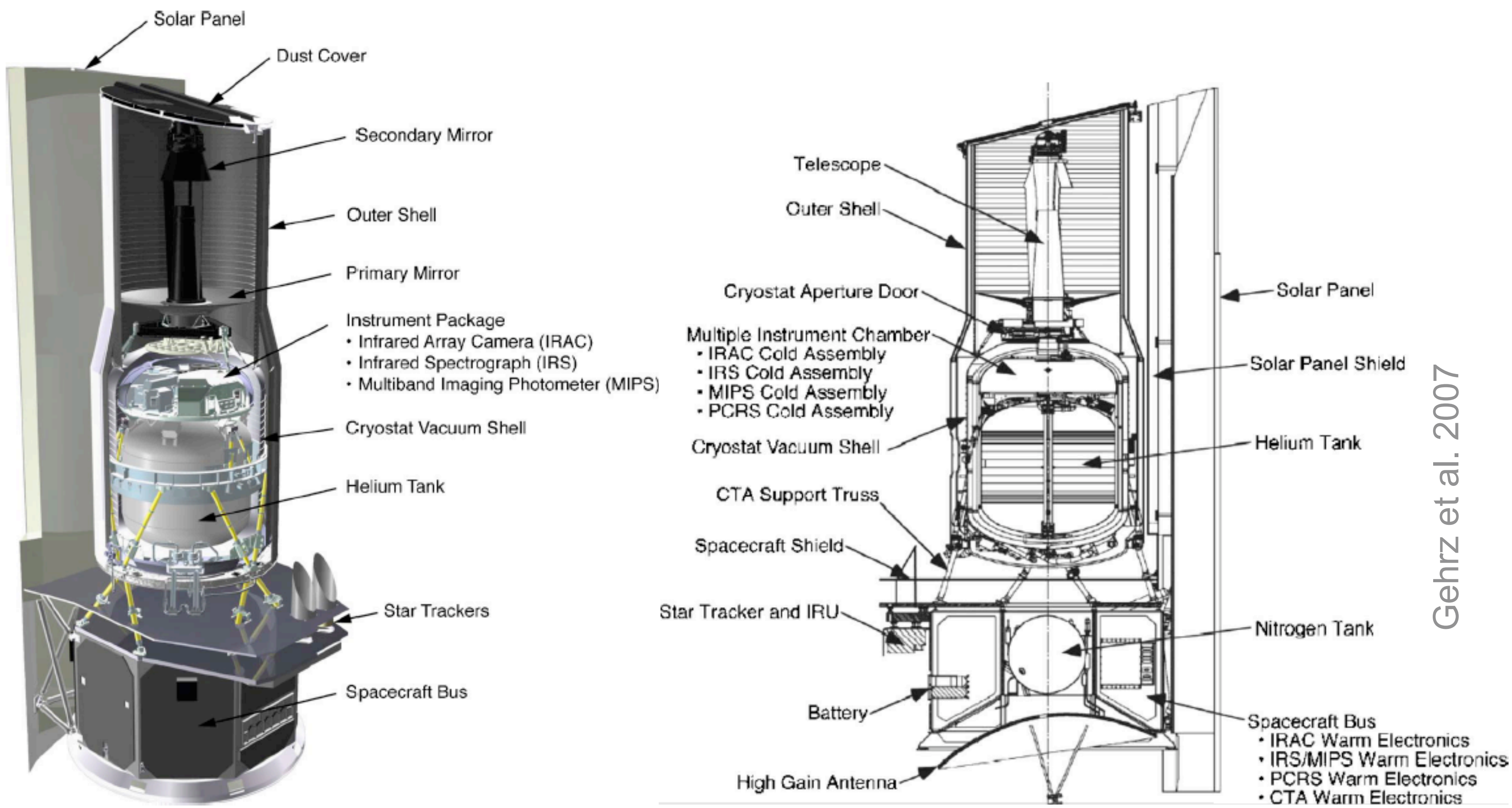
Spitzer Space Telescope's Infrared Array Camera



NASA

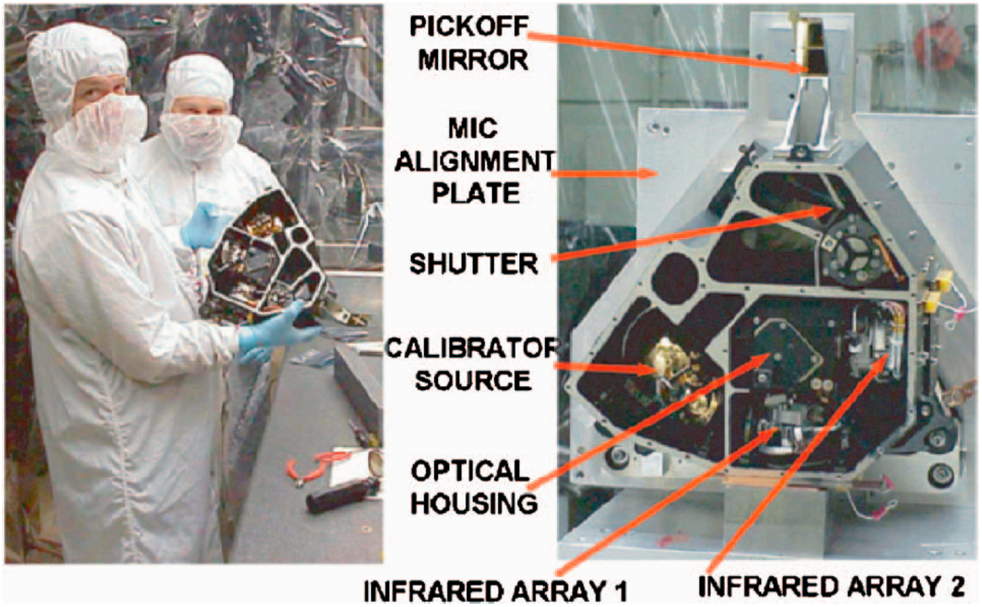
Launch of the *SST* from the KSFC
on 2003 August 25 UT.

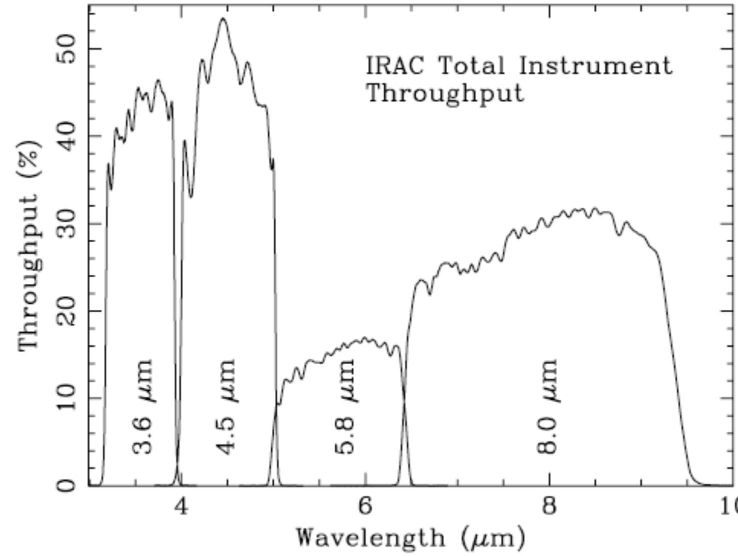
This artist rendition shows an external view of the *Spitzer Space Telescope* in its Earth-trailing solar orbit. The 85-cm cryogenically cooled beryllium Ritchey-Chretien telescope system operates at temperatures as low as 5.5 K.

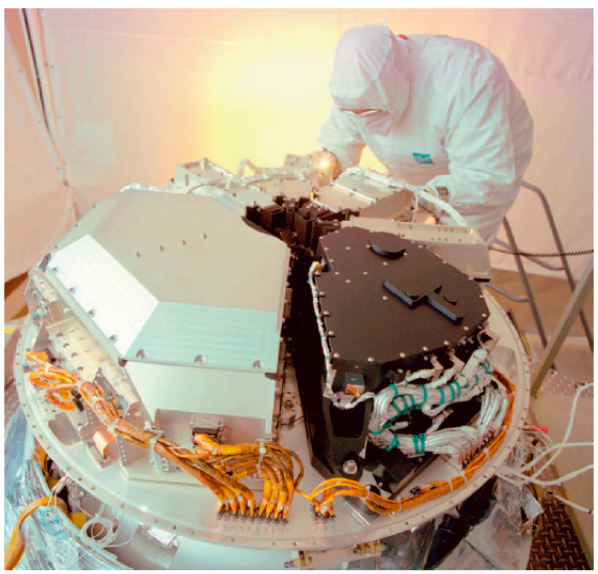


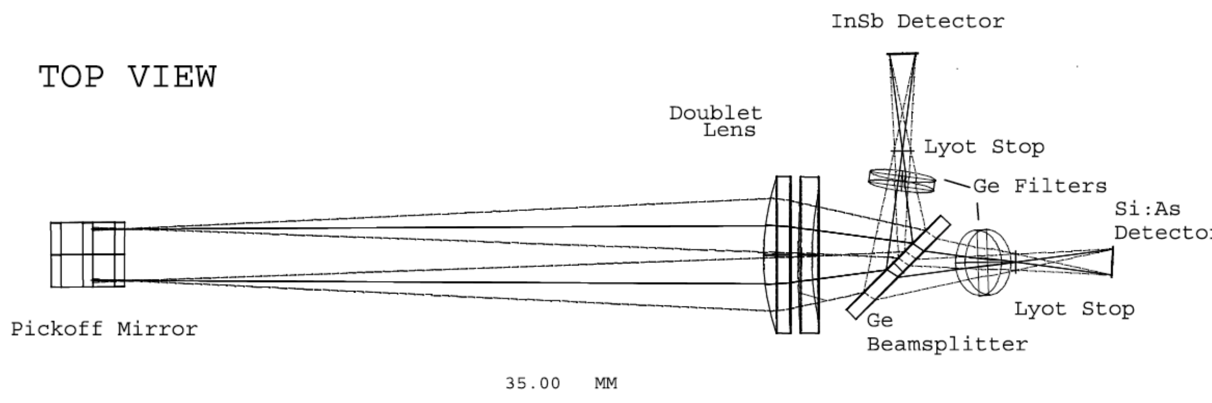
Internal view and side-view schematic of the *SST.*

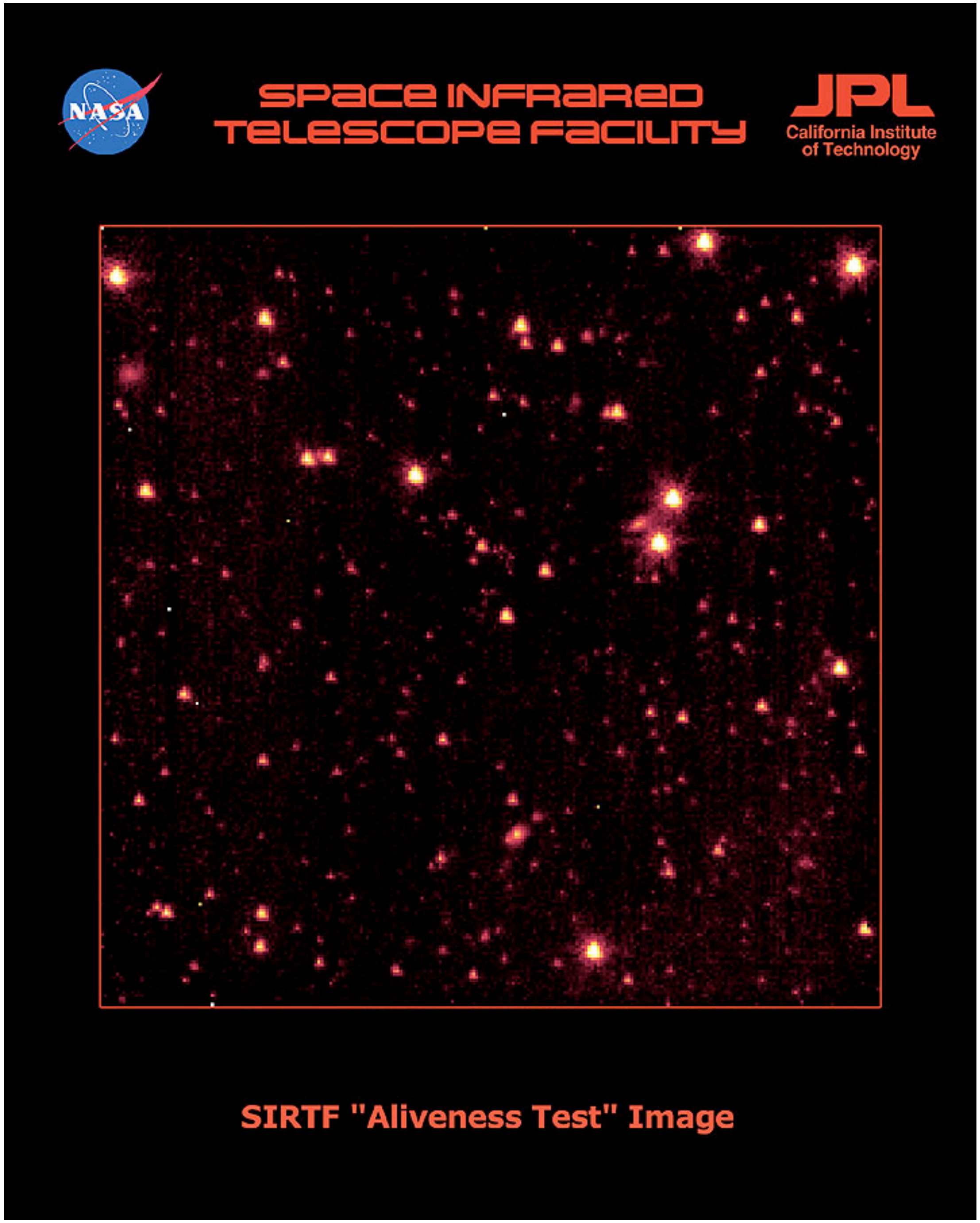
IRAC: Infrared Array Camera

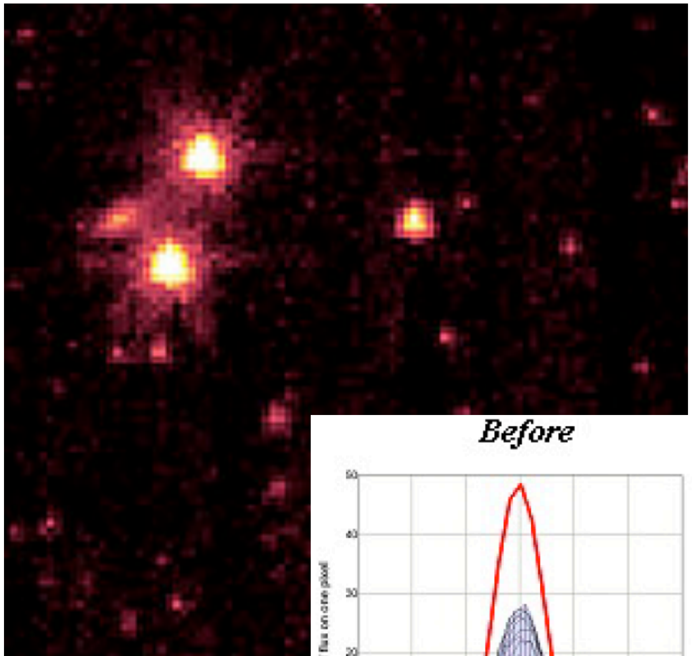


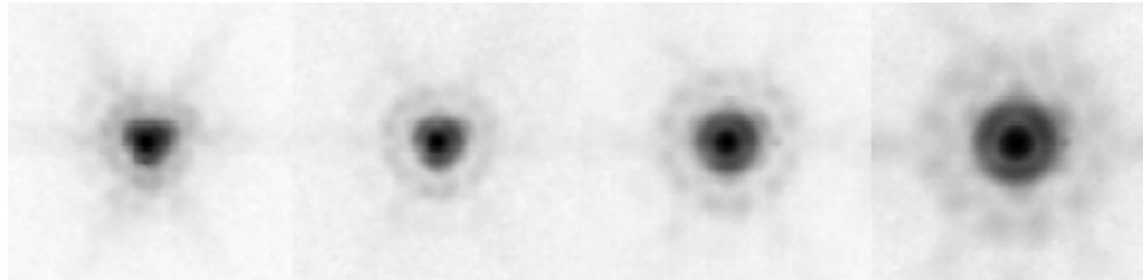




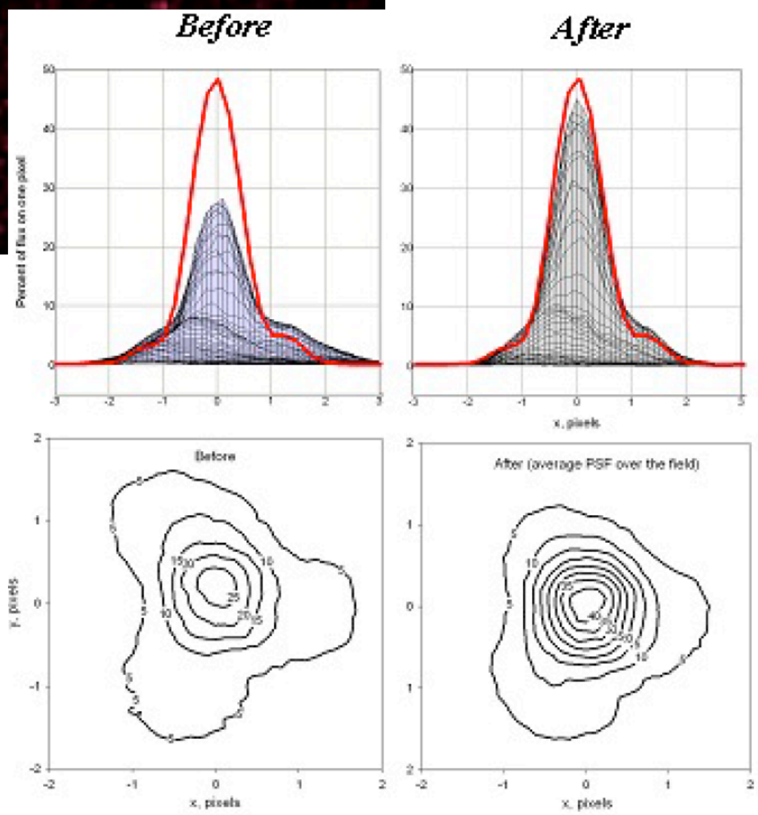


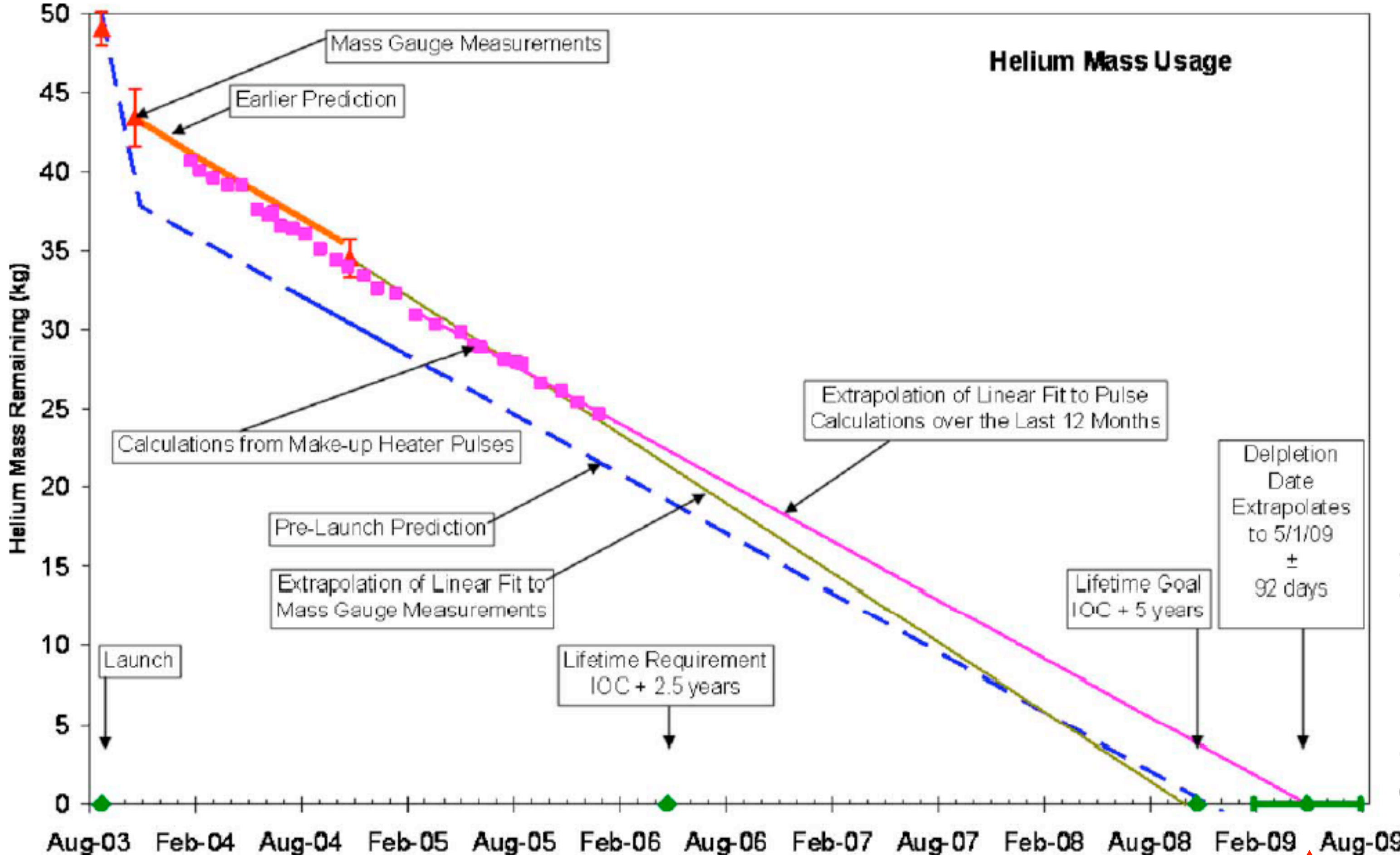

NASA
SPACE INFRARED
TELESCOPE FACILITY
JPL
California Institute
of Technology
SIRTF "Aliveness Test" Image





3.6 μm 4.5 μm 5.8 μm 8.0 μm





Gehrz et al. 2007

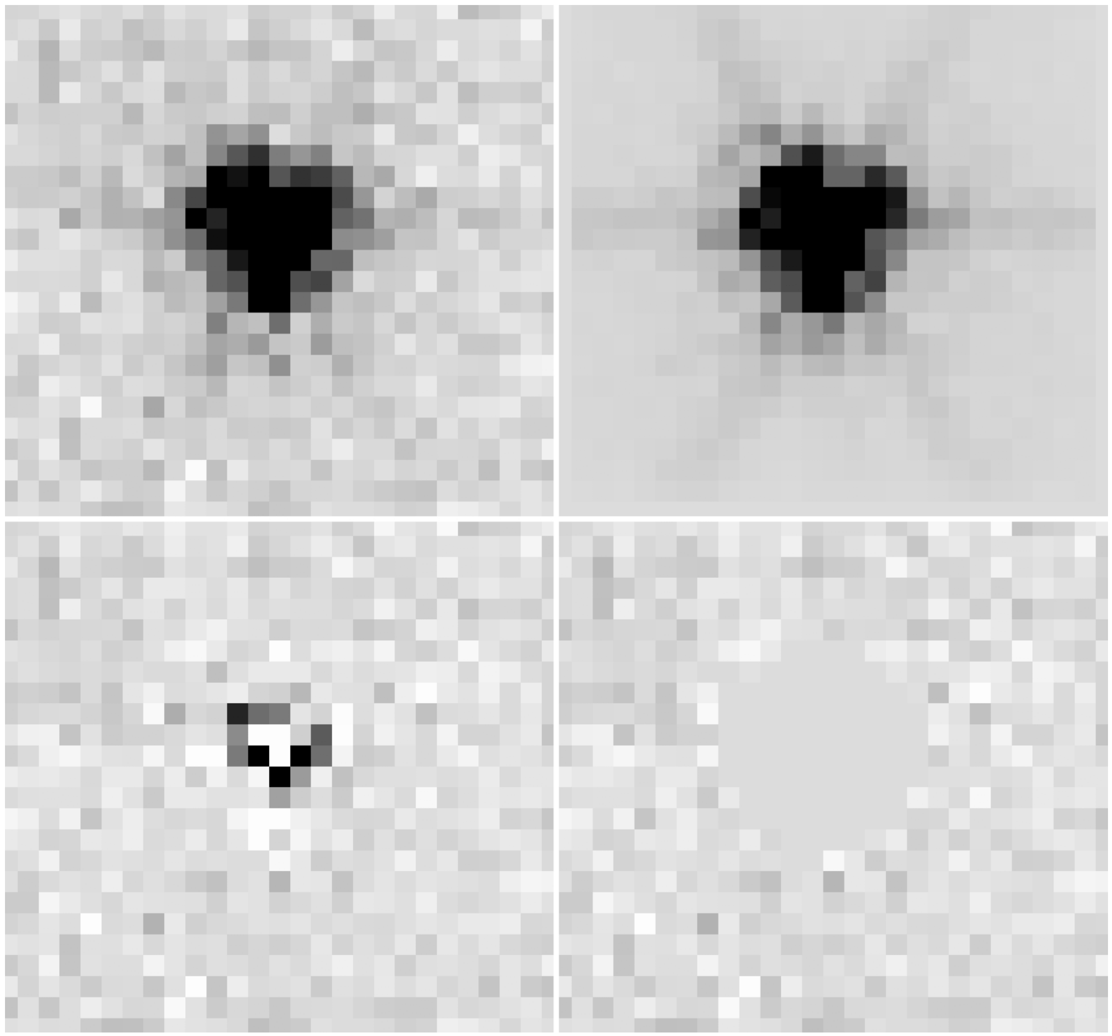
April 2009

nominal start of Spitzer’s Warm Mission

Instrument Status

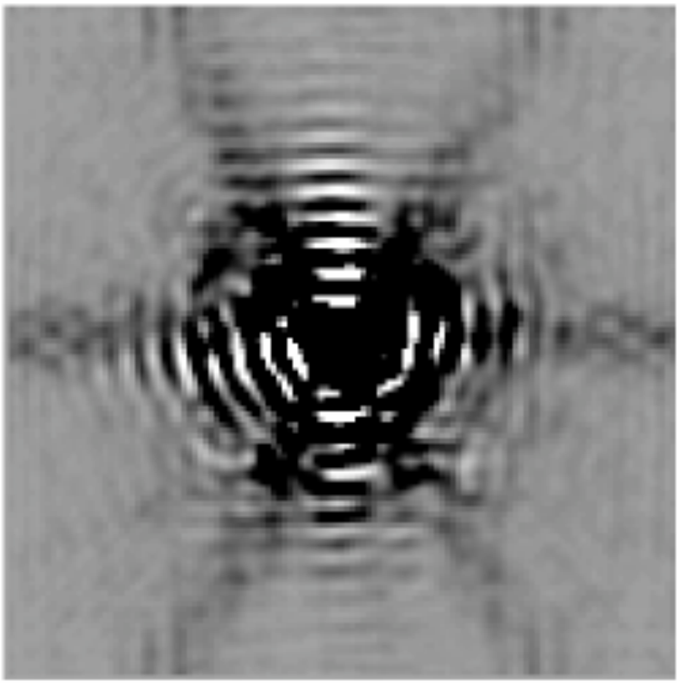
Instrument	Today	Warm Mission
IRAC Infrared Array Camera Ch1 (3.6 μm) & Ch2 (4.5 μm)	✔	✔
IRAC Infrared Array Camera Ch3 (5.8 μm) & Ch4 (8.0 μm)	✔	✘
IRS Infrared Spectrograph	✔	✘
MIPS Multiband Imaging Photometer	✔	✘

MATPHOT Photometry



IRAC Ch1 PSF (5x5 theoretical)

linear stretch



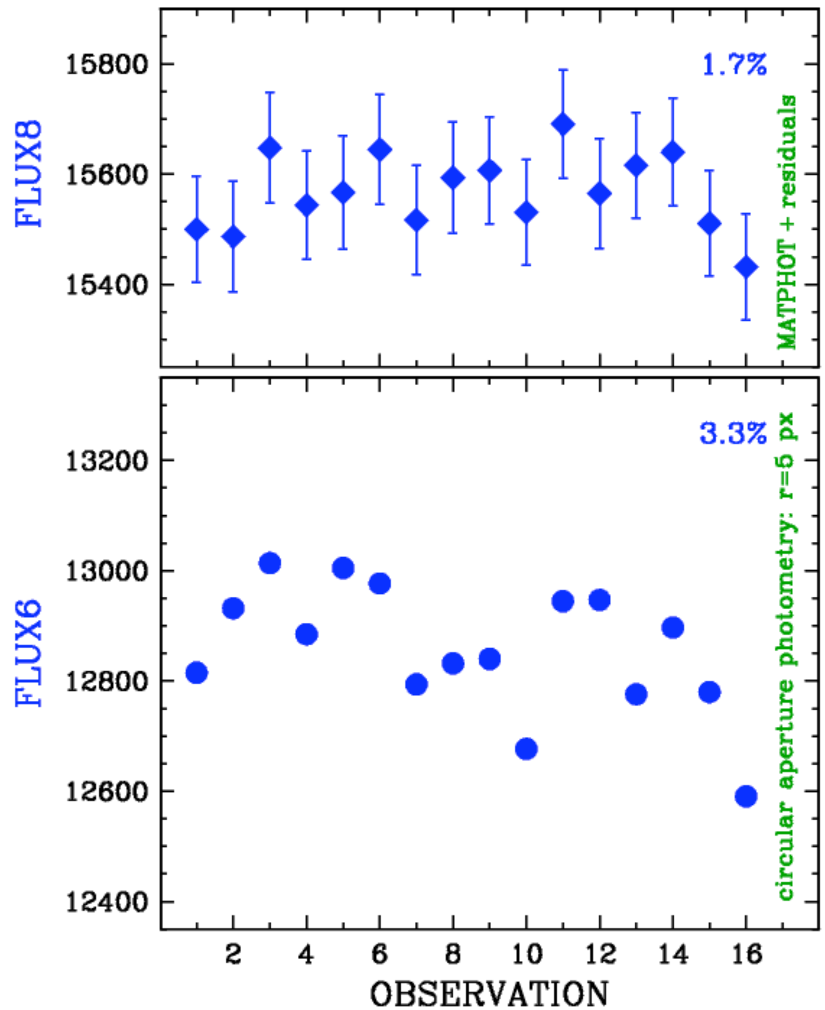
logarithmic stretch

Source: Bill Hoffmann
(U. of Arizona, IRAC team member)

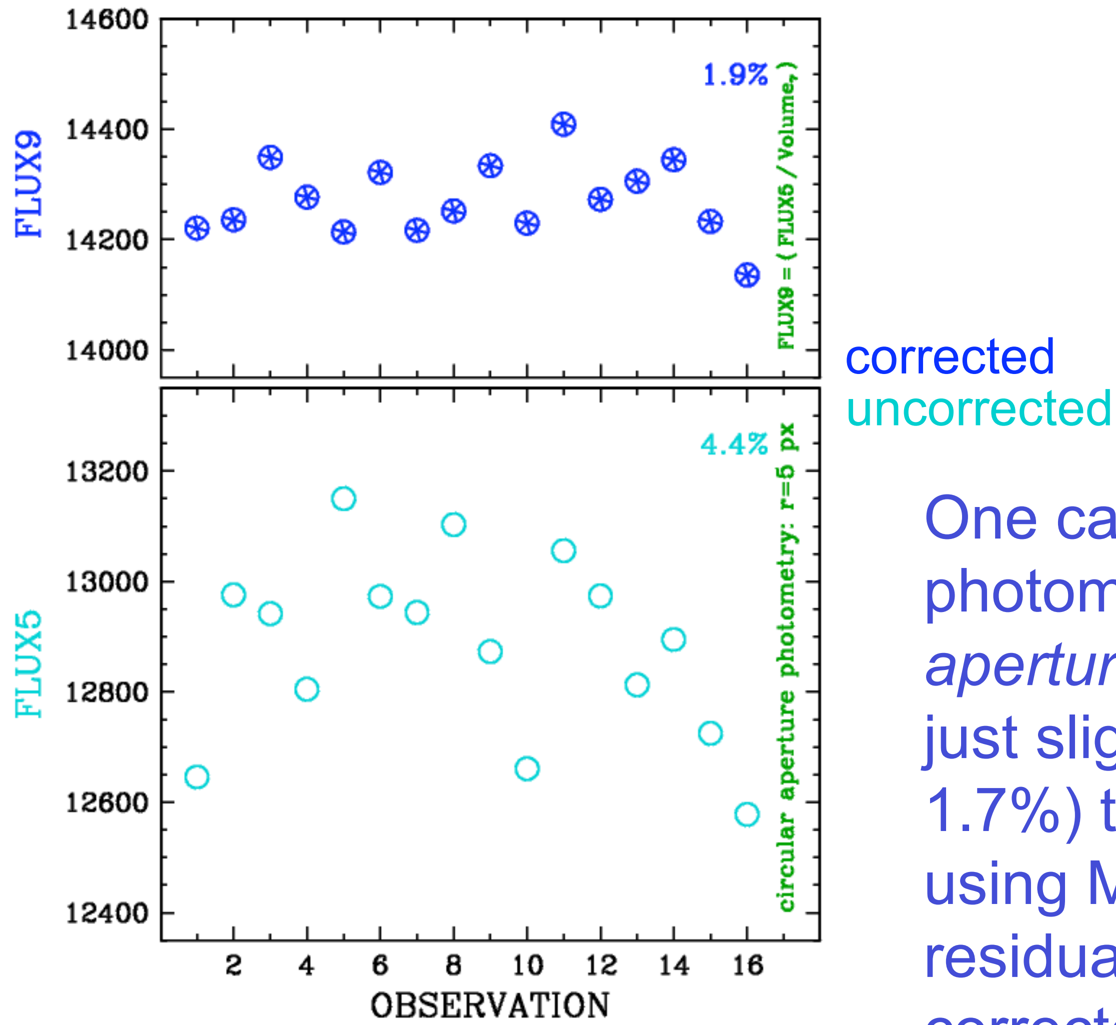
Relative Intrapixel QE Variation of IRAC Ch1

$$\mathrm{intrapix} = \begin{pmatrix} 0.813 & 0.875 & 0.875 & 0.875 & 0.813 \\ 0.875 & 1.000 & 1.000 & 1.000 & 0.875 \\ 0.875 & 1.000 & 1.000 & 1.000 & 0.875 \\ 0.875 & 1.000 & 1.000 & 1.000 & 0.875 \\ 0.813 & 0.875 & 0.875 & 0.875 & 0.813 \end{pmatrix}$$

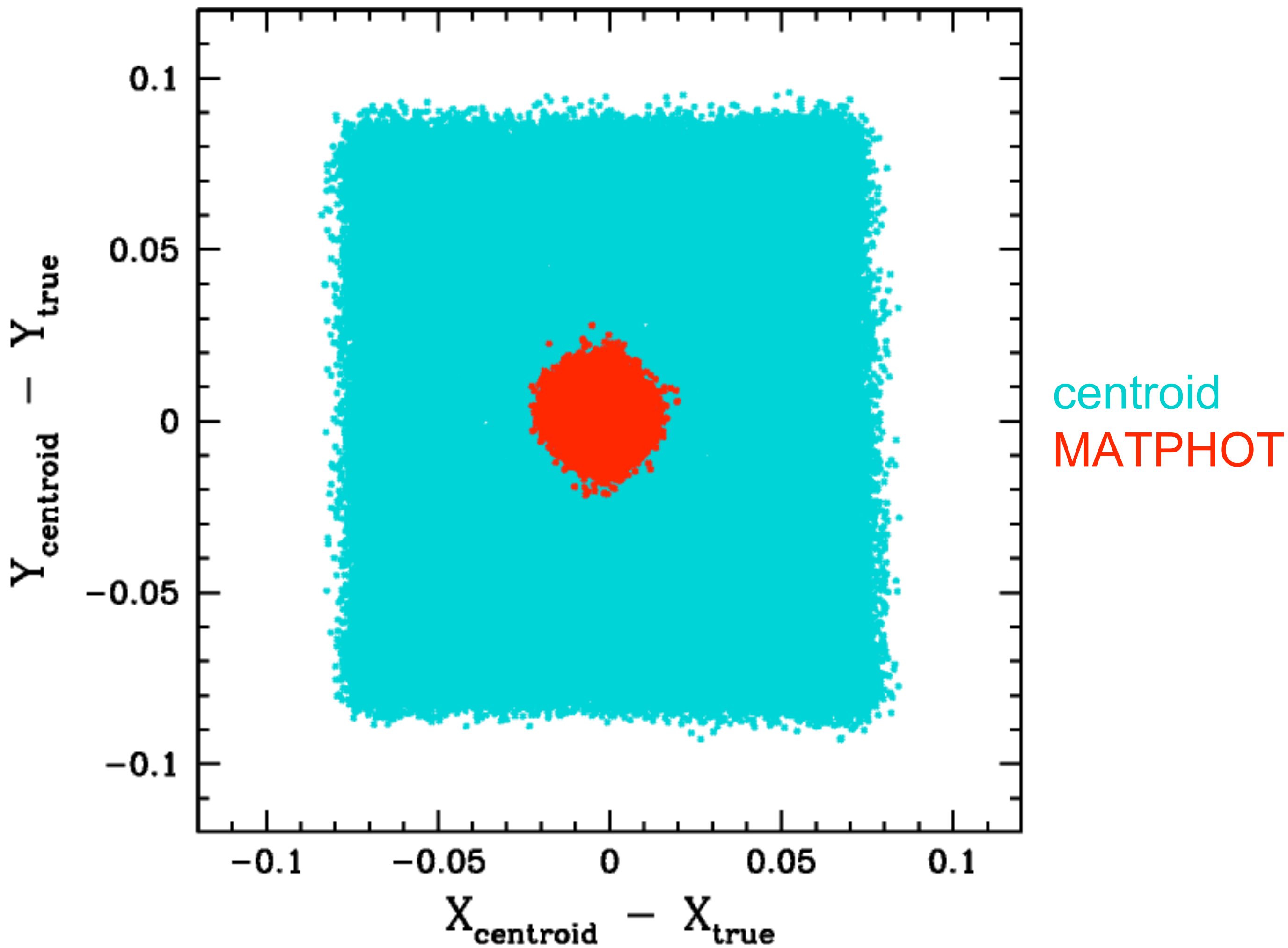
Source: Bill Hoffmann
(U. of Arizona, IRAC team member)



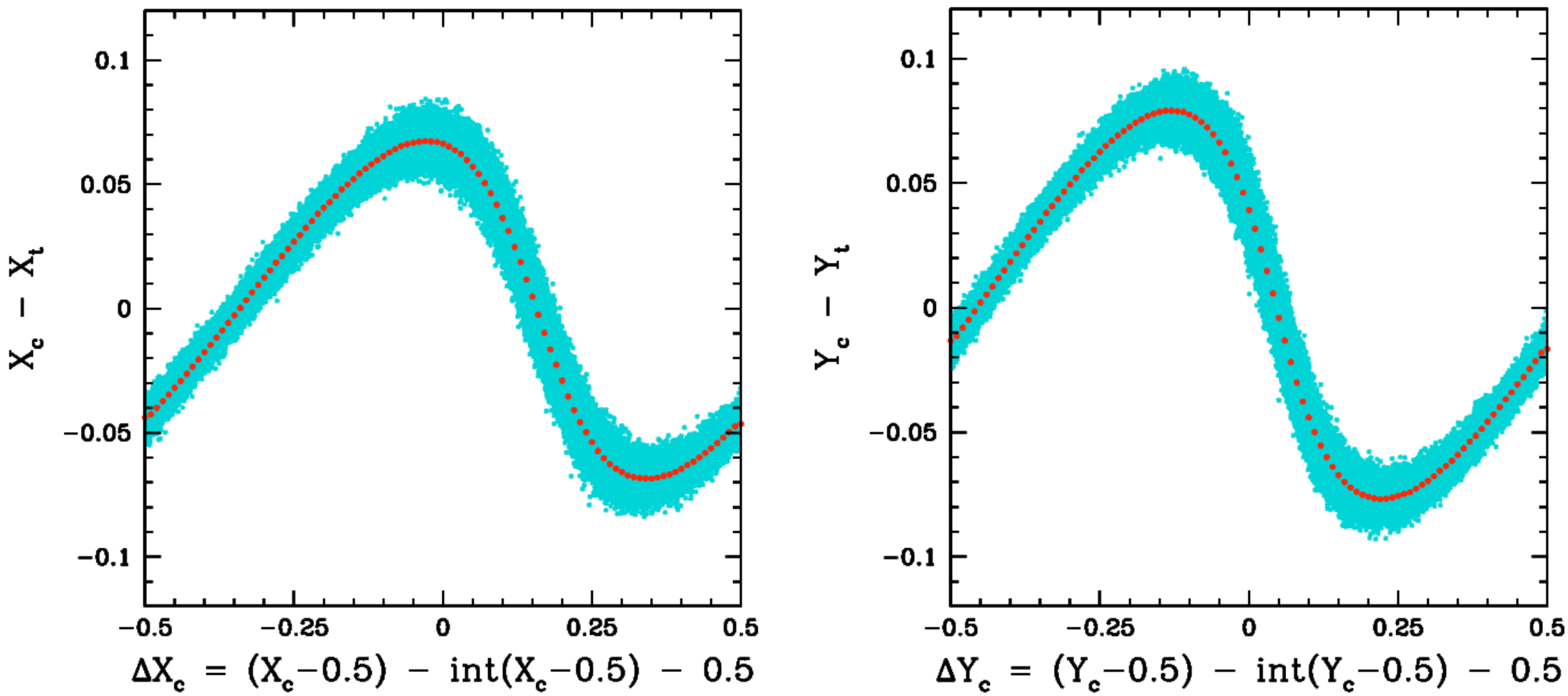
The relative peak-to-peak spread in independent photometric measurements decreased by a factor of 1.9 (3.3% to 1.7%) over the best results from aperture photometry using MATPHOT with residuals; the relative robust standard deviation is reduced by a factor of 1.7 (0.92% to 0.54%).



One can obtain stellar photometric precision with *aperture photometry* which is just slightly worse (1.9% vs. 1.7%) than the best results using MATPHOT with residuals – if raw fluxes are corrected with MATPHOT computed Sampled Point Response Function volumes.

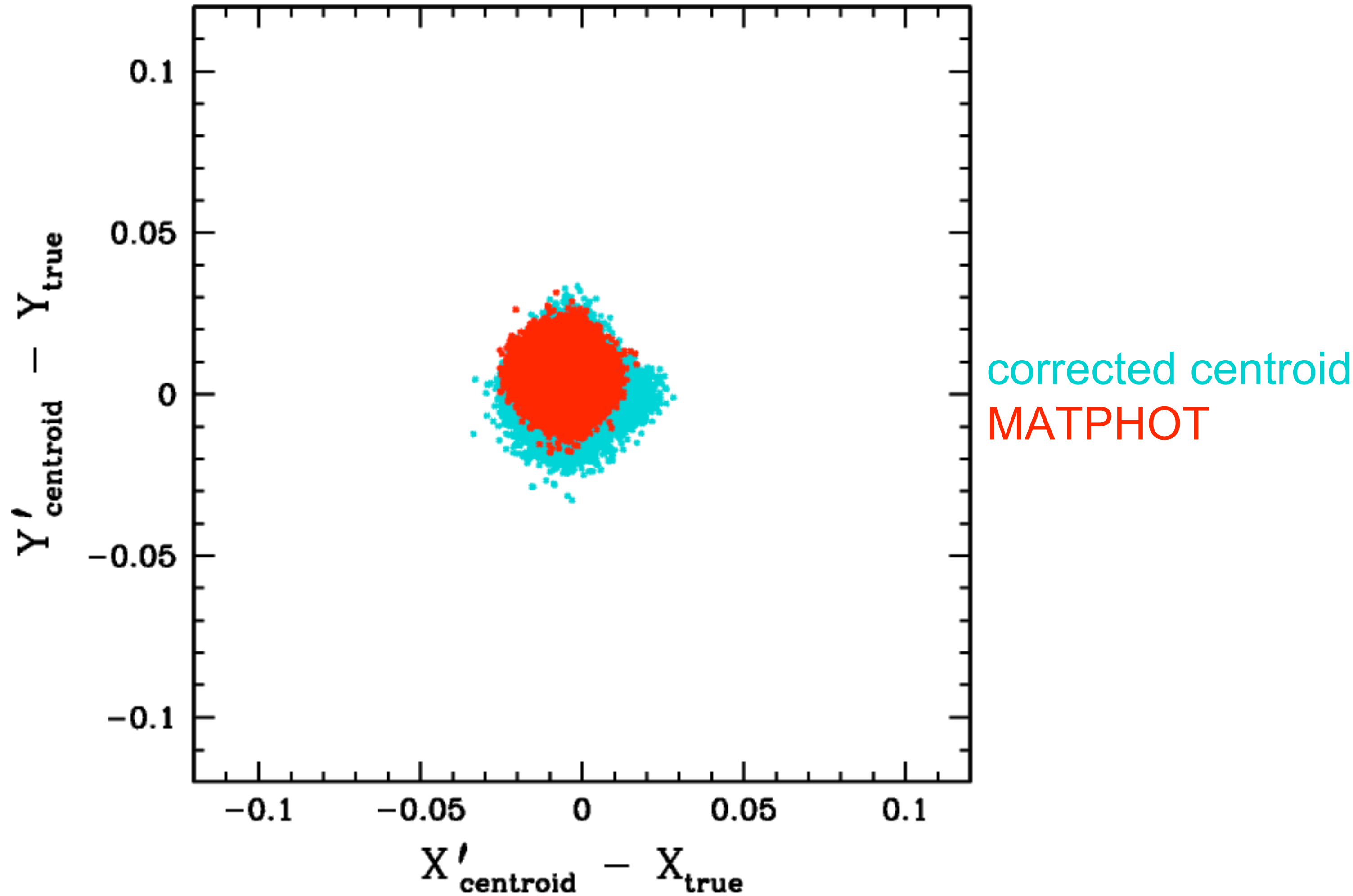


Problem: Large ***systematic*** errors with intensity-weighted mean positions!



Solution: Systematic position errors are separable in X and Y!

Determine median differences as a function of offsets in X and Y.



Much better!

Now almost as good as the ideal MATPHOT results!

IRAC Data Handbook

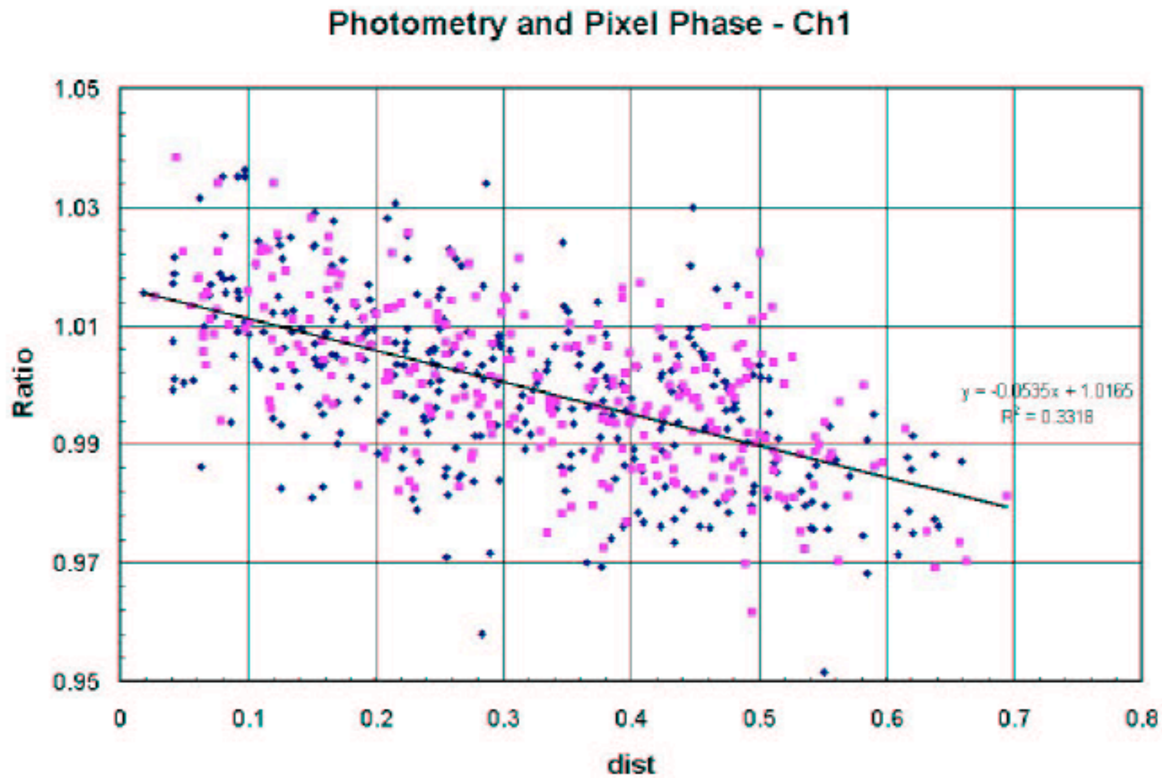
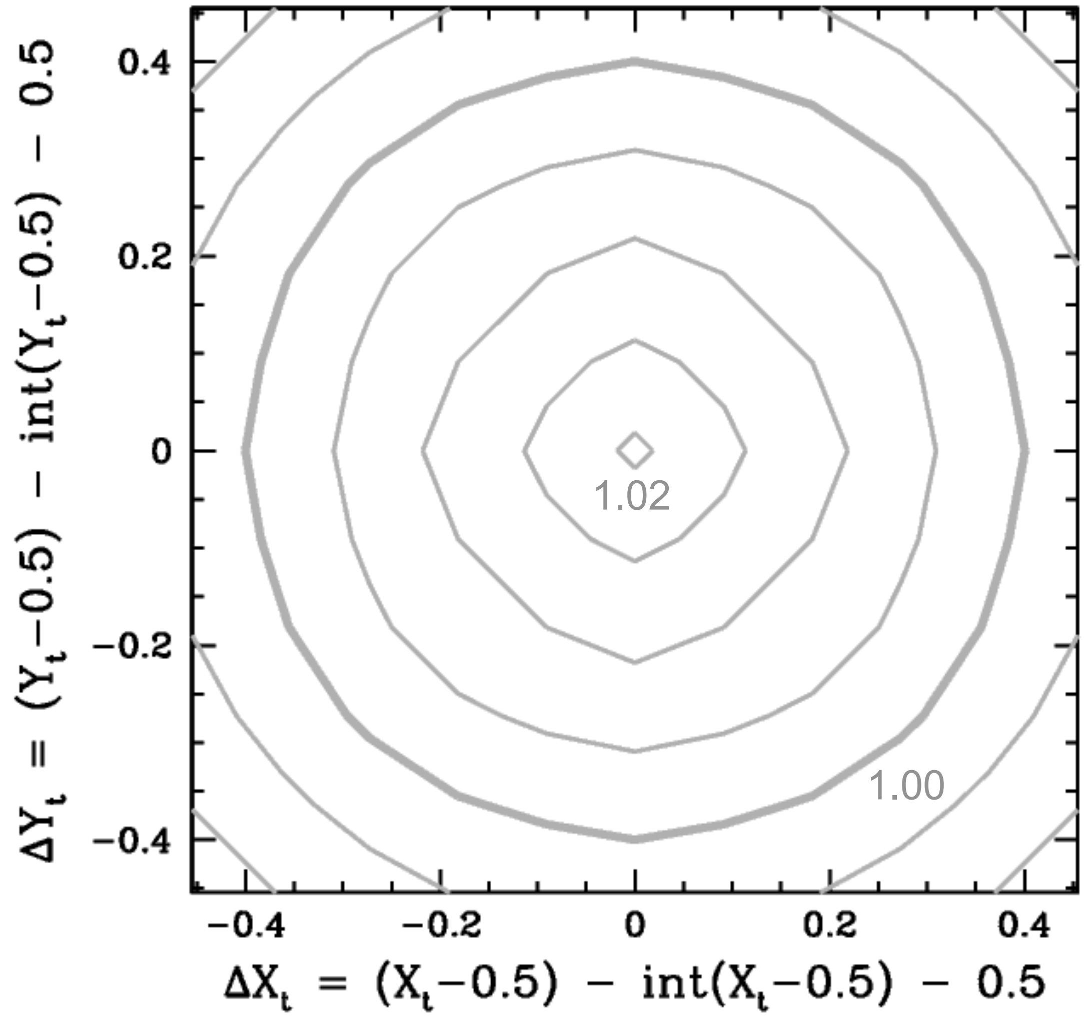
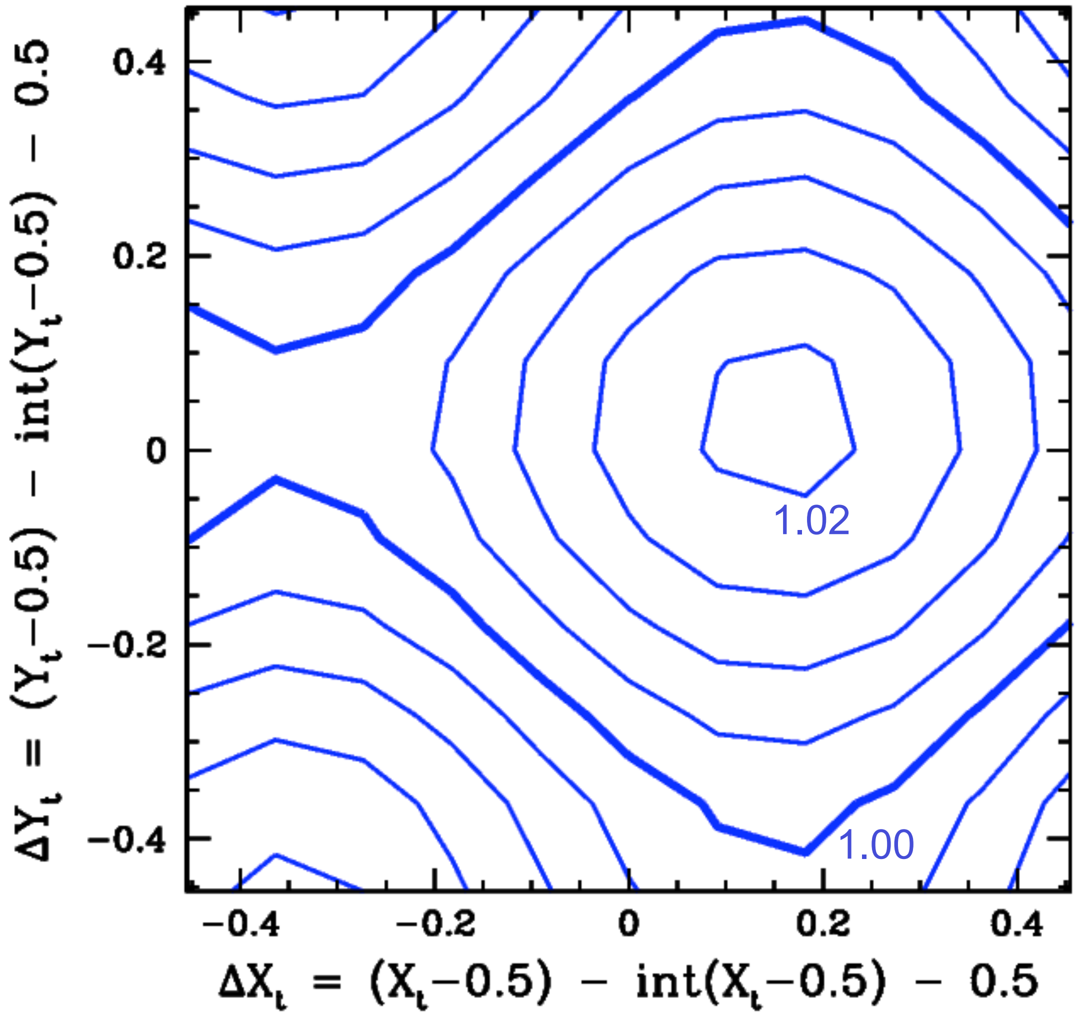


Figure 5.1: Dependence of point source photometry on the distance of the centroid of a point source from the nearest pixel center in channel 1. The ratio on the vertical axis is the measured flux density to the mean value for the star, and the quantity on the horizontal axis is the fractional distance of the centroid from the nearest pixel center.



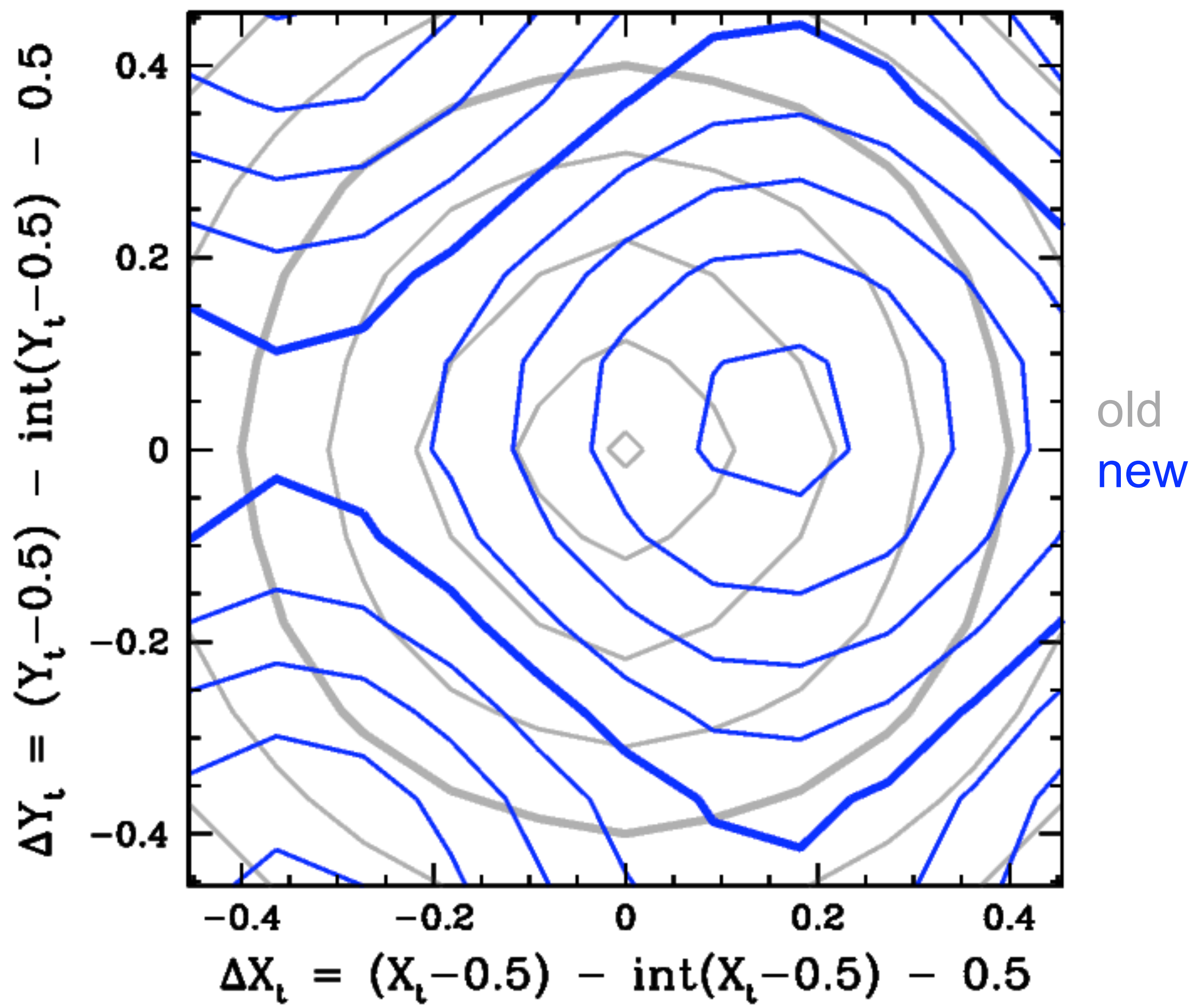
old

Recommended aperture correction
from the IRAC Data Handbook
as a function of X and Y offsets.

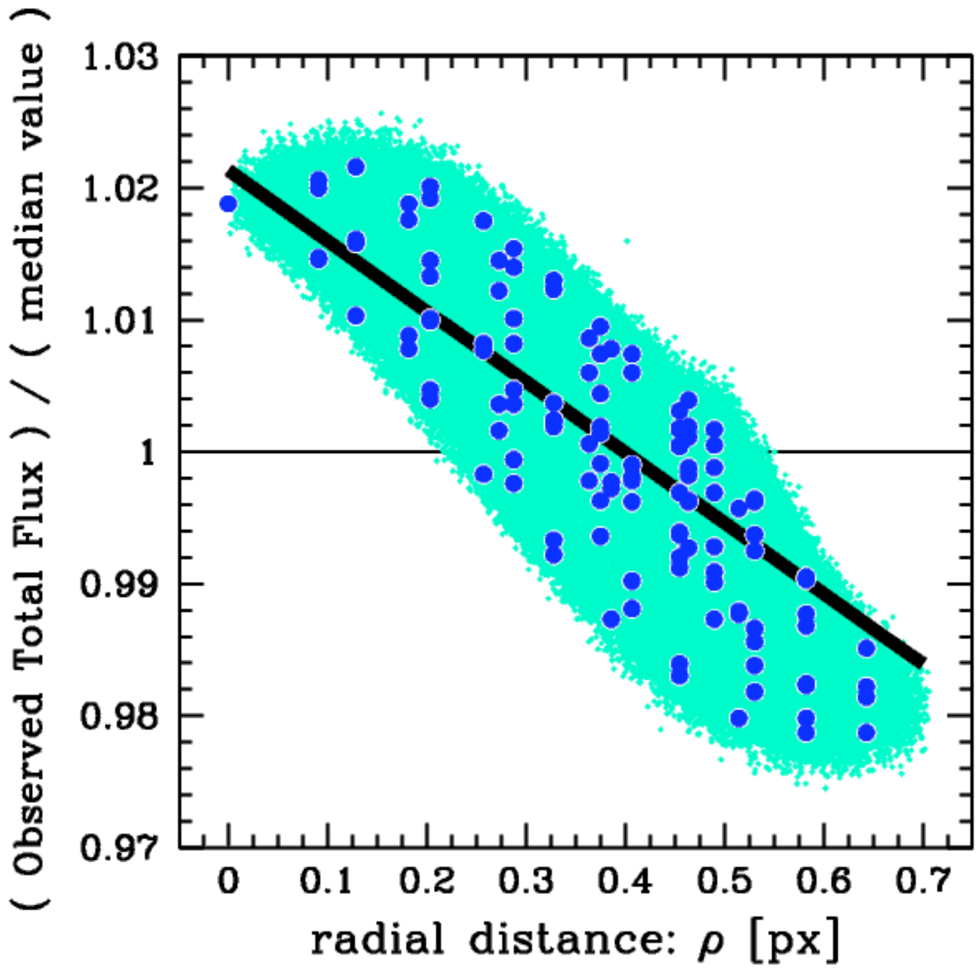


new

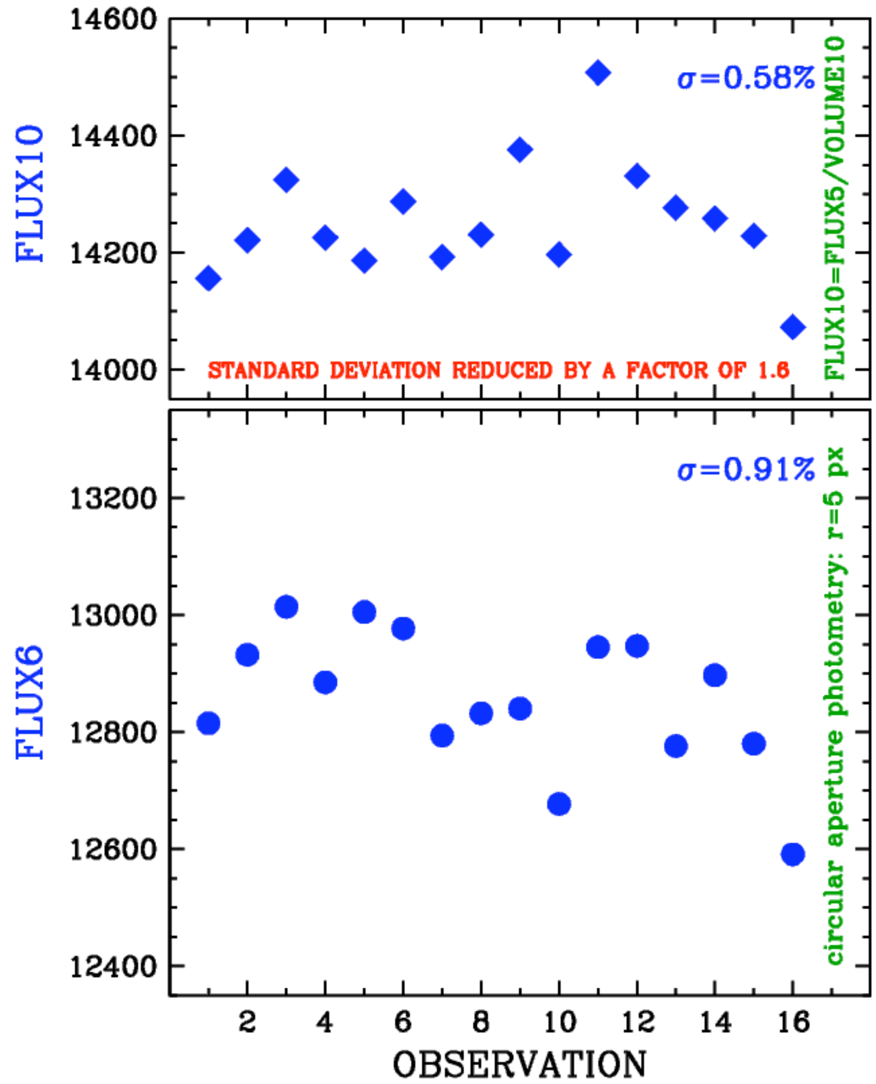
New aperture correction



0.4
0.2
0
−0.2
−0.4
−0.4
−0.2
0
0.2
0.4
$\Delta X_t = (X_t - 0.5) - \mathrm{int}(X_t - 0.5) - 0.5$
$\Delta Y_t = (Y_t - 0.5) - \mathrm{int}(Y_t - 0.5) - 0.5$
old
new

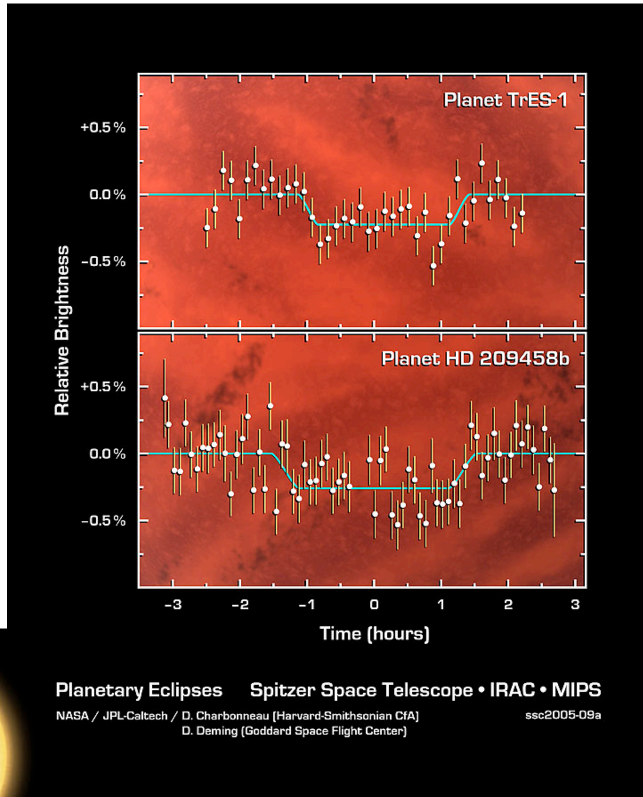


The new two-dimensional correction (*blue points*) with the standard radial correction (*black line*).

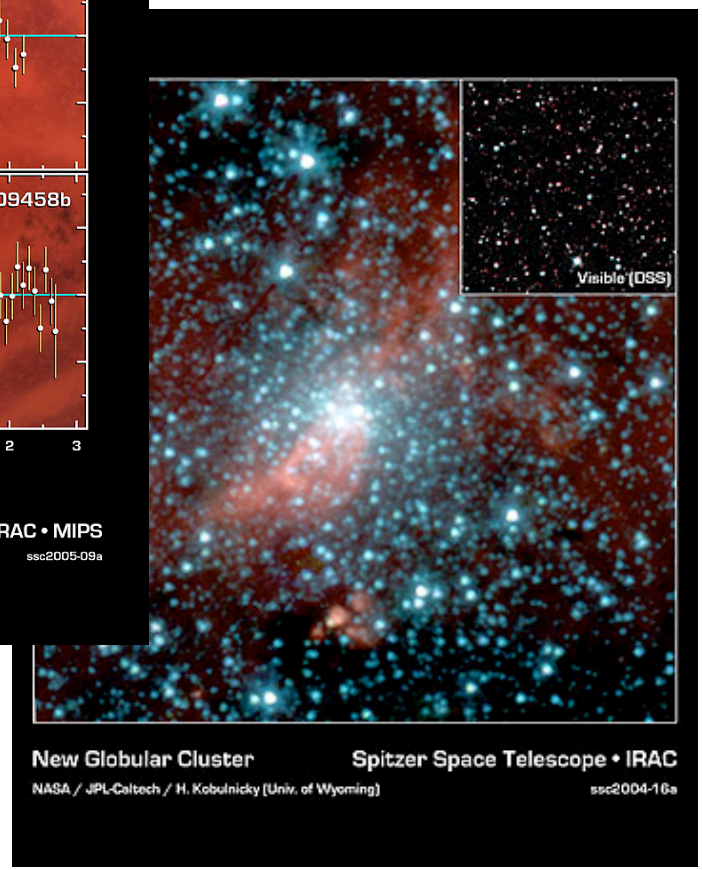


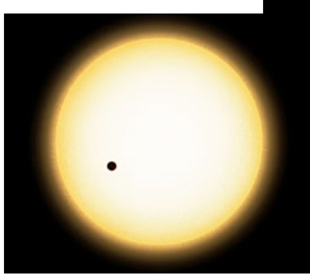
In the central region, the robust standard deviation decreased by a factor of 1.6 .

Improving the photometric precision of IRAC Ch1 and Ch2 point-source observations would enhance the science return of Spitzer's Warm Mission…



star clusters





exoplanets

and much more…

I am working closely with the IRAC Instrument Team on a Spitzer Cycle 4 archival grant which investigates the development of new calibration procedures for IRAC Ch1 and Ch2 that have the potential of significantly improving the precision of IRAC point-source photometry. This timely research effort is intended to not only enhance the science return of existing IRAC Ch1 and Ch2 observations in the Spitzer Data Archive but also those that might be made during the possible Spitzer Warm Mission.

Spitzer Space Telescope — Archival Research Proposal #40106.

Improving the Photometric Precision of IRAC Channels 1 & 2

Principal Investigator: Kenneth J Mighell
Institution: National Optical Astronomy Observatory (NOAO)
Electronic mail: mighell@noao.edu
Technical Contact: Kenneth J Mighell, National Optical Astronomy Observatory (NOAO)
Co-Investigators: William Hoffmann, Steward Observatory / University of Arizona
William Glaccum, Caltech/Spitzer Science Center
Science Category: Galactic: stellar populations

SPIE Astronomical Instrumentation

23 - 28 June 2008
Parc Chanot Marseille Congres & Expositions
Marseille France

Space Telescopes and Instrumentation I: Optical, Infrared, and Millimeter Wave 2008

Conference 7010 - Proceedings of SPIE Volume 7010
Dates: **Monday-Saturday 23 - 28 June 2008**

Improving the photometric precision of IRAC channel 1

Paper 7010-105
Author(s): Kenneth J. Mighell, National Optical Astronomy Observatory; William J. Glaccum, California Institute of Technology; William F. Hoffmann, The Univ. of Arizona/Steward Observatory

Planning is underway for a possible post-cryogenic mission with the Spitzer Space Telescope. Only Channels 1 and 2 (3.6 and 4.5 microns) of the Infrared Array Camera (IRAC) will be operational; they will have unmatched sensitivity from 3 to 5 microns until the James Webb Space Telescope is launched. At SPIE Orlando, Mighell described his NASA-funded MATPHOT algorithm for precision stellar photometry and astrometry and presented MATPHOT-based simulations that suggested Channel 1 stellar photometry may be significantly improved by modeling the nonuniform RQE within each pixel, which, when not taken into account in aperture photometry, causes the derived flux to vary according to where the centroid falls within a single pixel (the pixel-phase effect). We analyze archival observations of calibration stars and compare the precision of stellar aperture photometry, with 1-dimensional and 2-dimensional pixel-phase flux corrections, and MATPHOT-based PSF-fitting photometry which accounts for the observed loss of stellar flux due to the nonuniform intrapixel quantum efficiency. We show how the precision of aperture photometry of bright stars corrected with a 2-dimensional correction function can yield photometry that is almost as precise as that produced by PSF-fitting procedures. This timely research effort is intended to enhance the science return not only of observations already in Spitzer data archive but also those that will be made during the Spitzer Warm Mission.

CRBLASTER

A Fast Parallel-Processing Program for Cosmic-Ray Rejection

PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, 113:1420–1427, 2001 November

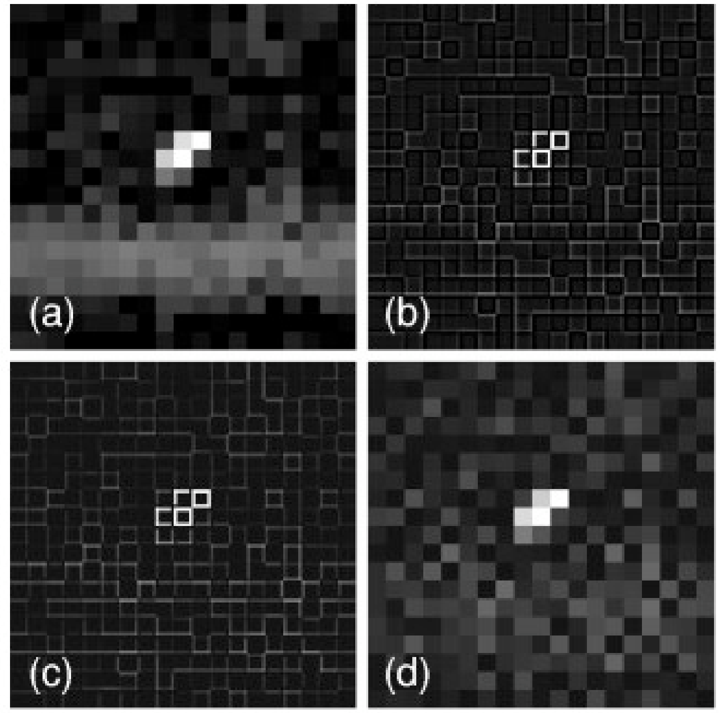
Cosmic-Ray Rejection by Laplacian Edge Detection

PIETER G. VAN DOKKUM[1]
California Institute of Technology, MS 105-24, Pasadena, CA 91125; pgd@astro.caltech.edu

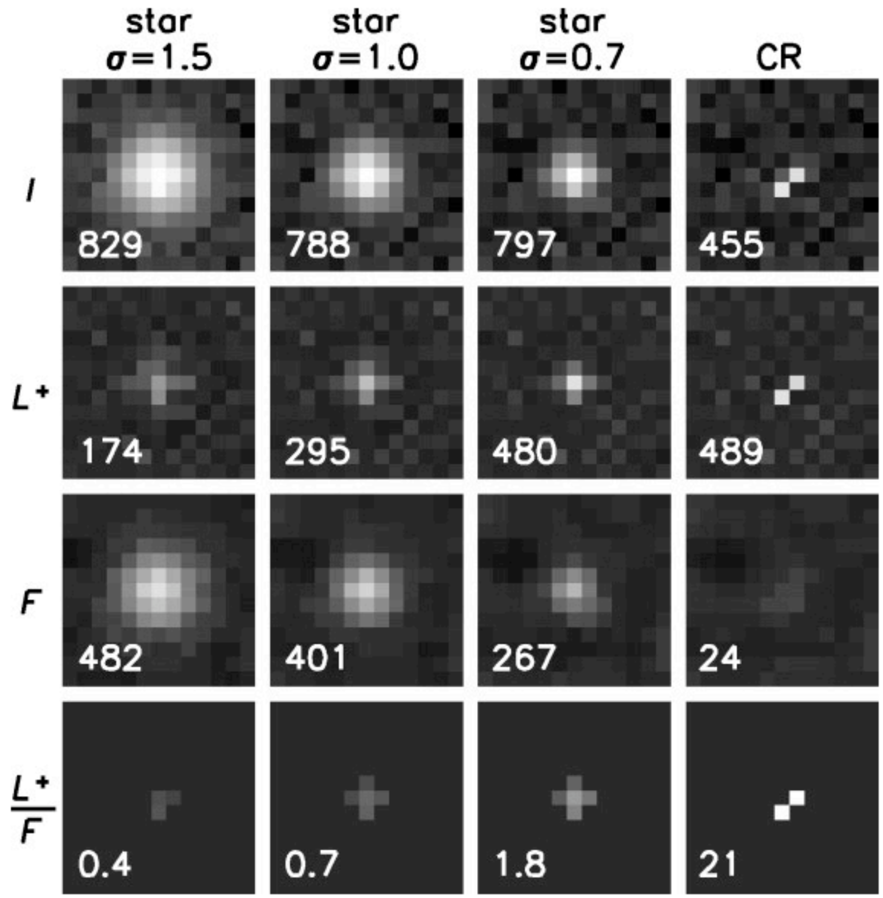
Received 2001 May 1; accepted 2001 July 31

ABSTRACT. Conventional algorithms for rejecting cosmic rays in single CCD exposures rely on the contrast between cosmic rays and their surroundings and may produce erroneous results if the point-spread function is smaller than the largest cosmic rays. This paper describes a robust algorithm for cosmic-ray rejection, based on a variation of Laplacian edge detection. The algorithm identifies cosmic rays of arbitrary shapes and sizes by the sharpness of their edges and reliably discriminates between poorly sampled point sources and cosmic rays. Examples of its performance are given for spectroscopic and imaging data, including *Hubble Space Telescope* Wide Field Planetary Camera 2 images.

Illustration of Laplacian edge detection. The original image is shown in (*a*). Panel *b* shows the same image after subsampling by a factor of 6 and convolution with the Laplacian kernel. Edges are positive on the inside of the cosmic ray and negative on the outside. Negative pixels are set to zero in (*c*), and the image is block-averaged to its original resolution in (*d*).

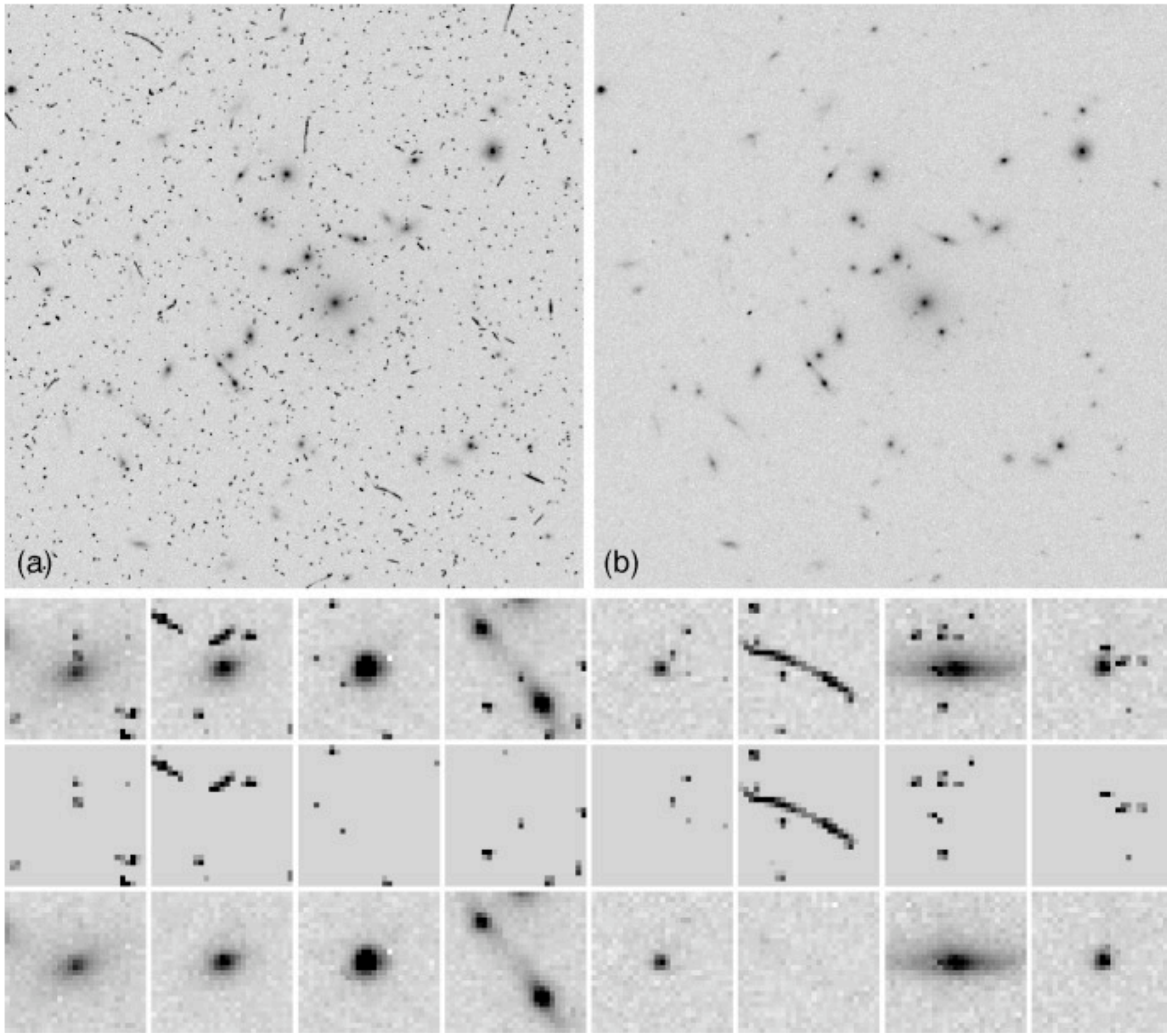


van Dokkum 2001



van Dokkum 2001

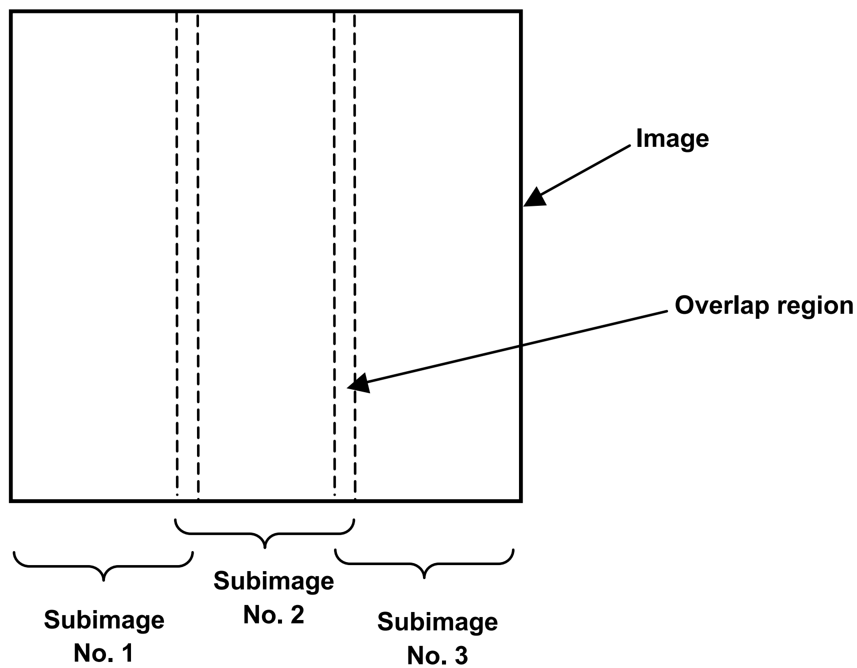
Differentiating between marginally sampled point sources and cosmic rays. The panels show, from top to bottom, artificial images of stars and a cosmic ray (I), the Laplacian of these images ($\mathcal{L}^+$), their fine-structure image ($\mathcal{F}$), and the Laplacian divided by the fine structure ($\mathcal{L}^+/\mathcal{F}$). The number in each panel is the value of the highest pixel. The highest pixels in the Laplacian images of the undersampled star ($\sigma = 0.7$ pixels) and the cosmic ray are similar. However, they are very different after division by the fine-structure image.

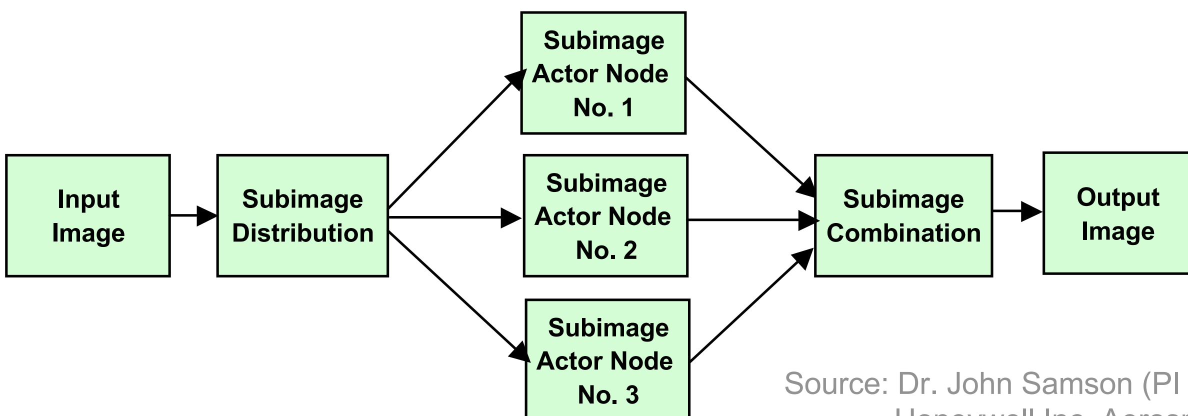


van Dokkum 2001

(*a*) *HST* WFPC2 image of galaxy cluster MS 1137+67. The restoration by L.A.COSMIC is shown in (*b*). The small panels show close-ups for a selection of stars and galaxies in various WFPC2 images. The algorithm leaves stars intact and is able to remove cosmic rays of arbitrary shapes and sizes.

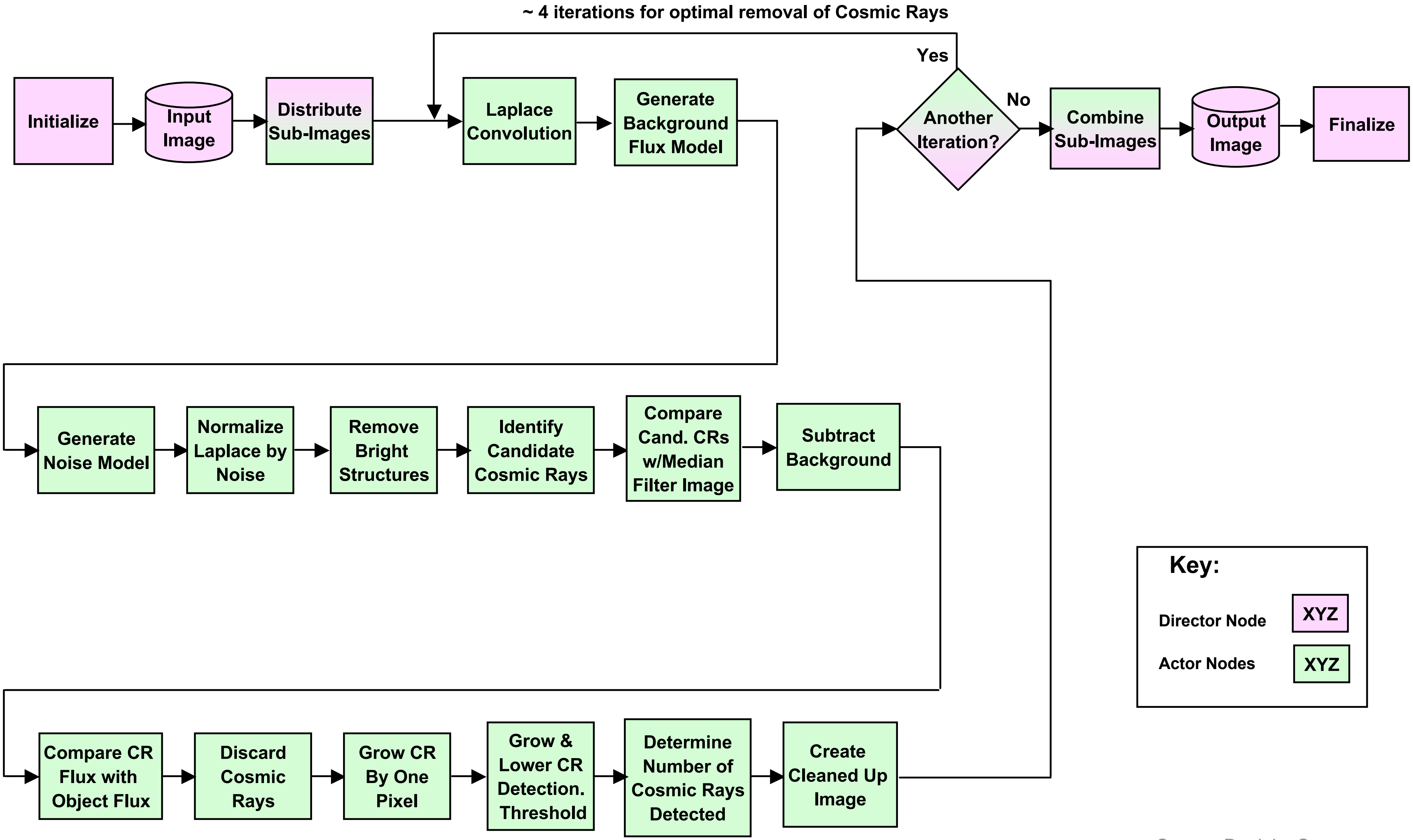
CRBLASTER Parallelization



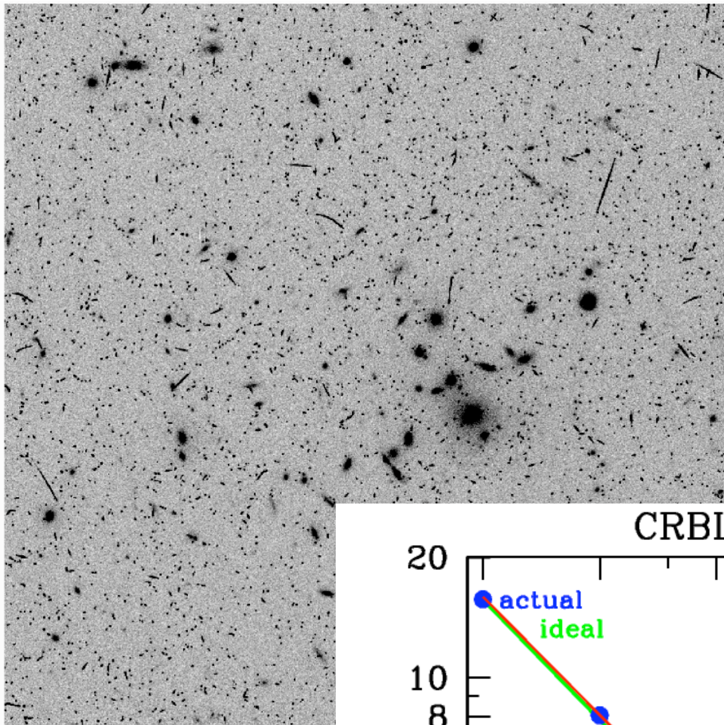


Source: Dr. John Samson (PI of NMP ST8 DM Project)
Honeywell Inc, Aerospace Systems

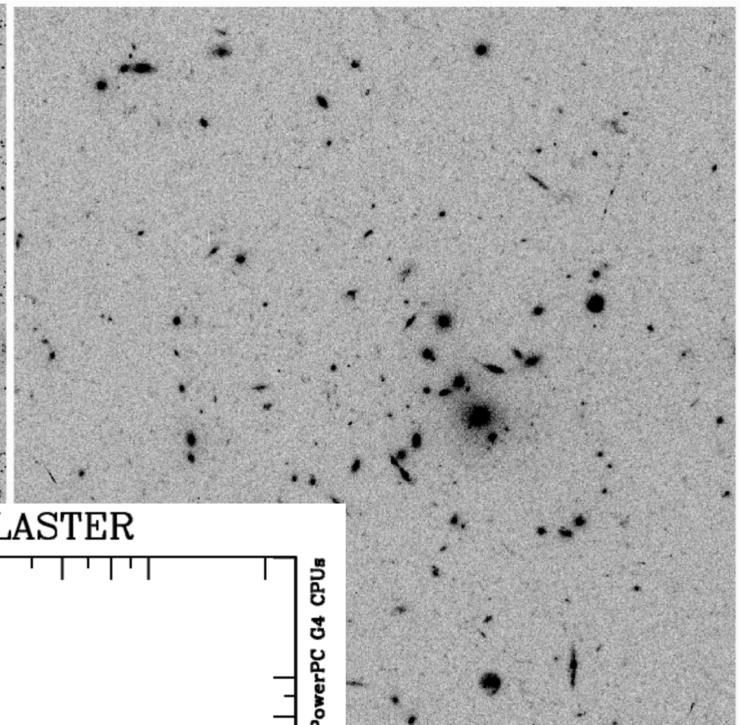
CRBLASTER Flow Diagram



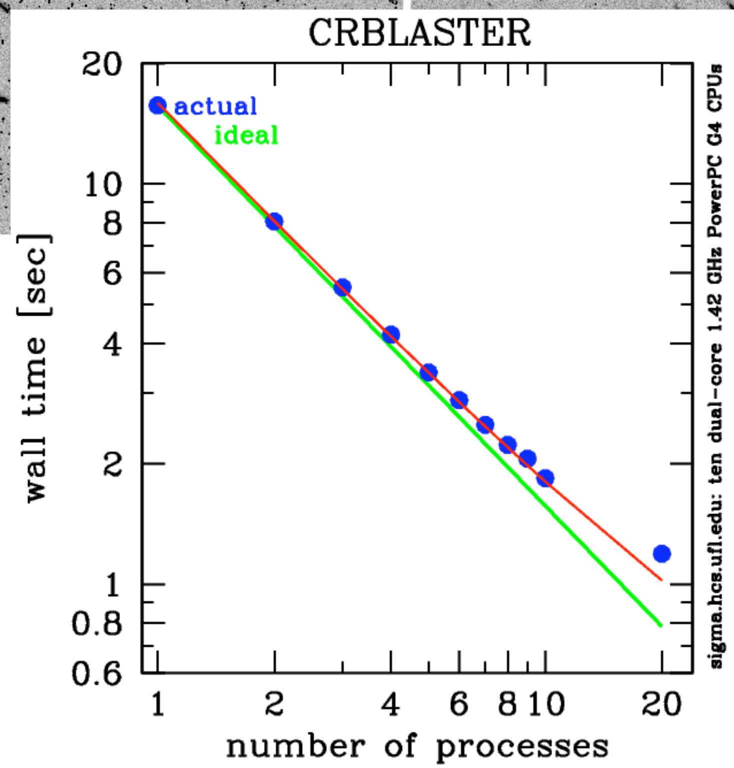
Source: Dr. John Samson

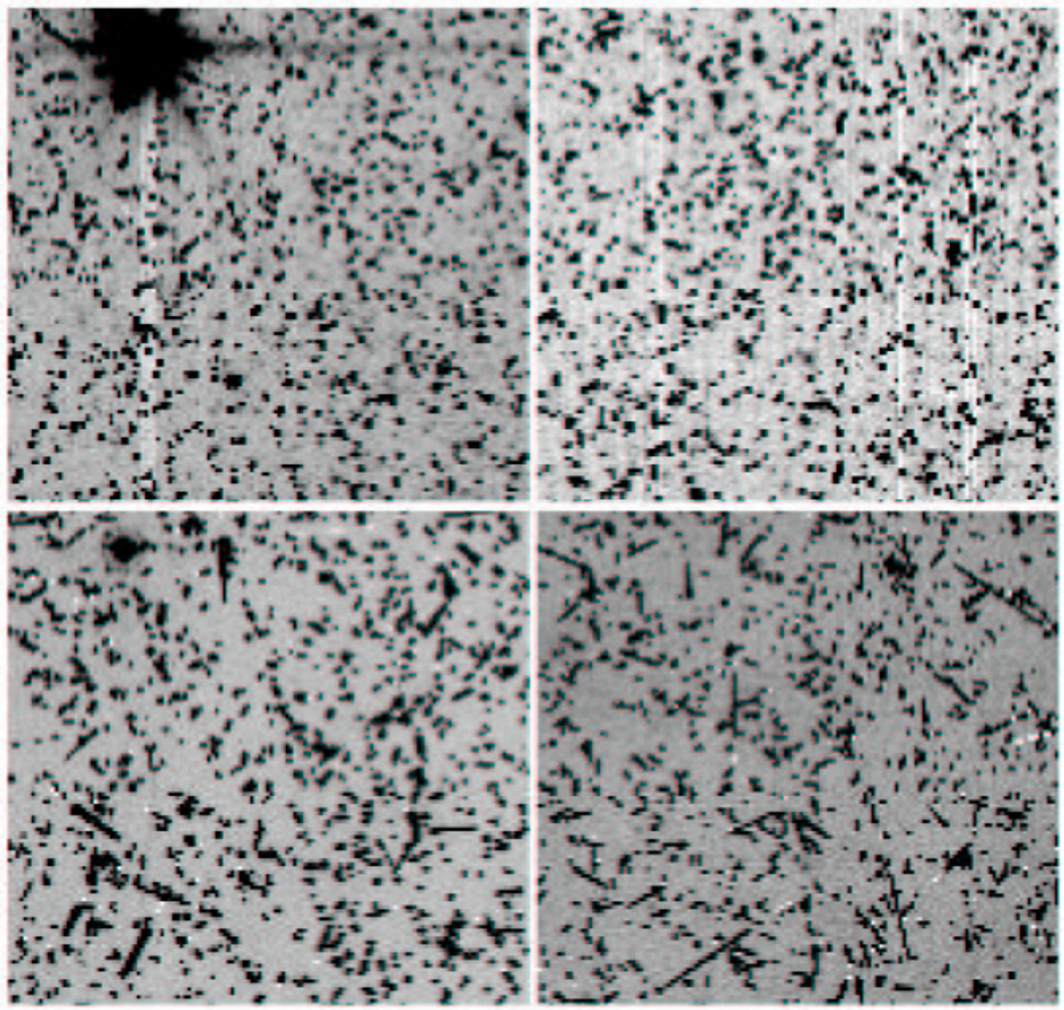


before



after





IRAC Data Handbook

Figure 4.19: The central 128×128 pixels of IRAC 12-second images taken on January 20, 2005 during a major solar proton event. Channels 1 and 2 are top left and top right; channels 3 and 4 are bottom left and bottom right. Except for the bright star in channels 1 and 3, almost every other source in these images is a cosmic ray. These data are from observations in pid 3126.

SPIE Astronomical Instrumentation

23 - 28 June 2008
Parc Chanot Marseille Congres & Expositions
Marseille France

Advanced Software and Control for Astronomy

Conference 7019 - Proceedings of SPIE Volume 7019
Dates: **Thursday-Saturday 26 - 28 June 2008**

CRFIND: a fast parallel-processing program for cosmic ray rejection

Paper 7019-55
Author(s): Kenneth J. Mighell, National Optical Astronomy Observatory

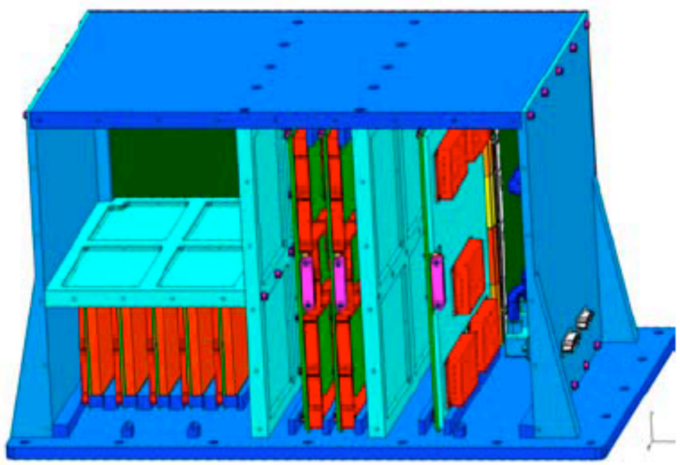
Many astronomical image analysis tasks are based on algorithms that can be described as being "embarrassingly parallel", where the analysis of one subimage generally does not affect the analysis of another subimage. Yet few parallel-processing astrophysical image-analysis programs exist that can easily take full advantage of today's fast multi-core servers costing a few thousands of dollars. The main reason for the shortage of state-of-the-art parallel-processing astrophysical image-analysis codes is that the writing of parallel codes has been perceived to be difficult. I describe a new fast parallel-processing image-analysis program called CRFIND which does cosmic ray rejection using van Dokkum's L.A.Cosmic algorithm. CRFIND is written in C using the industry standard Message Passing Interface library. Processing a single 800x800 HST WFPC2 image takes 1.87 seconds using 4 processes on an Apple Xserve with two dual-core 3.0-GHz Intel Xeons; the efficiency of the program running with the 4 processors is 82%. The code can be used as a software framework for easy development of parallel-processing image-anlaysis programs using "embarrassing parallel" algorithms; all that needs to be done is to replace the core image processing task (in this case the C-version of the L.A.Cosmic algorithm) with an alternative image analysis task based on a single-processor algorithm. I describe the design and implementation of the program and then discuss how it could possibly be used to quickly do complex calibration tasks as part of the pipeline processing of images from large focal plane arrays.

NASA's New Millennium Program Space Technology 8 Dependable Multiprocessor Project Technology Readiness Level 6 Validation Effort

NASA NMP ST8 contract NMO-710209

Dr. John Samson, Honeywell Inc, Aerospace Systems
john.r.samson@honeywell.com

Dependable Multiprocessor Project Goal:
Develop for NASA the first supercomputer for space



PDR version

- 1 RHPPC SBC System Controller node
- 4 COTS DP nodes
- 1 Mass Storage node
- Gigabit Ethernet interconnect
- cPCI
- ST8 S/C interface
- Utility board
- Power Supply

DM Flight Hardware

- **Dimensions**
  - **10.6 x 12.2 x 18.0 in. (26.9 x 30.9 x 45.7 cm)**
- **Weight (Mass)**
  - **~ 42 lbs (19 kg)**
- **Power**
  - **~ 100 W**

Source: Dr. John Samson

Status of DM project

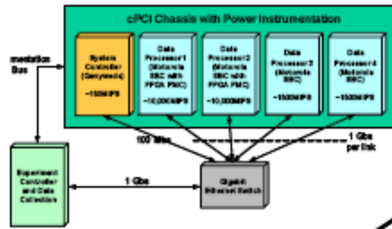
6/27/2007: ***Passed Critical Design Review*** – qualified for flight status

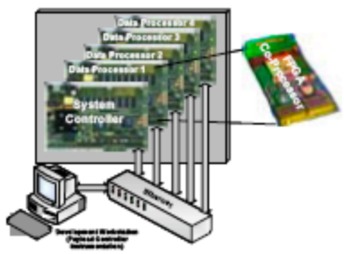
8/2007: NMP ST8 flight experiment eliminated

5/2008: ***Currently a candidate for next U.S. Air Force DSX launch***

7/30/2008: DM TRL6 Technology Validation Demonstration

Increasing system fidelity & integration



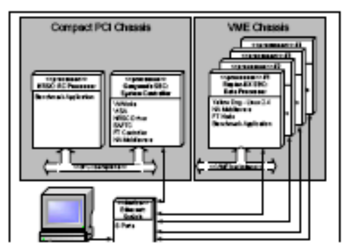


TRL4 Validation
- Demonstrated basic DM technologies in a laboratory environment on COTS hardware testbed including radiation source and sensor
  - Environment Sensor
  - Alert Generator
  - High Availability Middleware
  - Replication Services

TRL4 Technology Validation

NASA adds requirement for fault tolerant cluster and FT-MPI capability

TRL5 Technology Validation



TRL5 Validation
- Demonstrate basic DM technologies in a laboratory environment on testbed hardware with integrated Fault Tolerant Middleware Services
- Develop predictive models
- Validate and refine predictive models and predictive model parameters with experiment data
- partial set of canonical fault injection experiments

TRL6 Technology Validation

TRL6 Validation
- Demonstrate enhanced DM technologies in a laboratory environment on prototype flight hardware including exposure to radiation beam
- Validate and refine predictive models and predictive model parameters with experiment data
- complete set of canonical fault injection experiments

TRL7 Technology Validation

TRL7 Validation
- Dem... te DM techn... in space ...
- Validate ... models ... tive mode... ith exp...
- T... erime... w... identical to those performed during TRL6 validation and demonstration
- TRL7 experiments will be limited to technology elements which can only be validated in the space environment

NMP ST-8 flight experiment eliminated August 2007

Source: Dr. John Samson

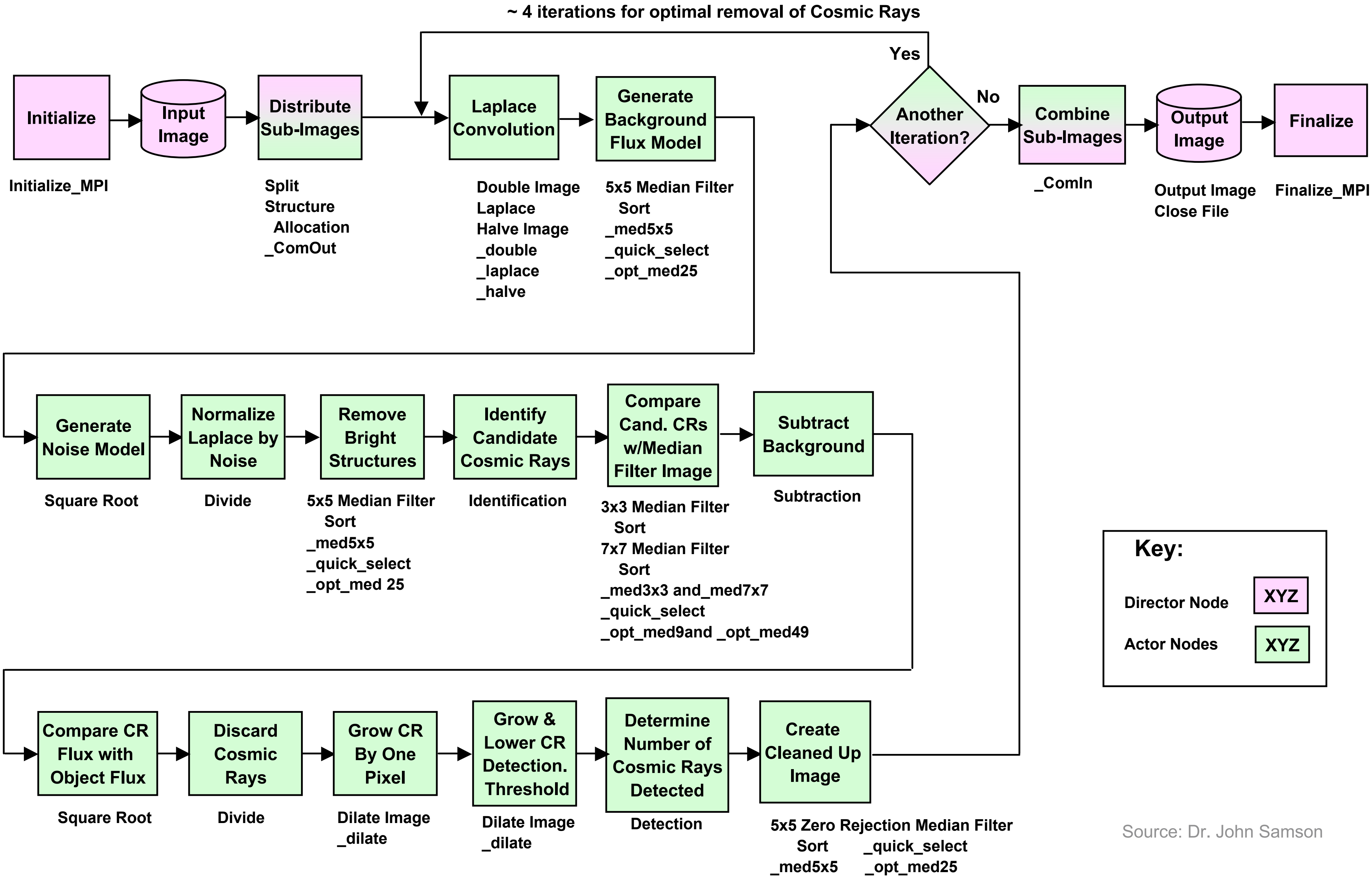
Dependable Multiprocessor Technology Validation Plan

CRBLASTER Application Overview

Application Developer:	**Dr. Ken Mighell (NOAO)**
DM TRL6 Purpose:	**Demonstrate real science application developed by an independent 3rd party with limited or no fault tolerance experience or expertise** - hybrid ABFT/replication - aggregate DM overhead no more than 50% - demonstrate scalability - demonstrate ease of porting from lab environment to DM
Real Science Application:	**Cosmic Ray elimination is a key function of virtually every astrophysics stellar photometry application** - based on Pieter van Dokkum's classic approach "Cosmic-Ray Rejection by Laplacian Edge Detection"
Future Application Target:	**James Webb Space Telescope (JWST)**
Input Data:	**Hubble Space Telescope (HST)** - 800 x 800 pixel image - double precision floating point
Output Data:	**Golden standard based on laboratory processing at NOAO**
Application Characteristics:	**Hybrid ABFT/Replication** - ~2500 SLOCs - MPI - ABFT protection on 2D Convolution function and Median Filters - in-ljne replication on non-ABFT-protectable functions - eminently scalable -- image subdivided into sub-images overlapped at edges to optimize parallelizability - check-points -- results after each iteration

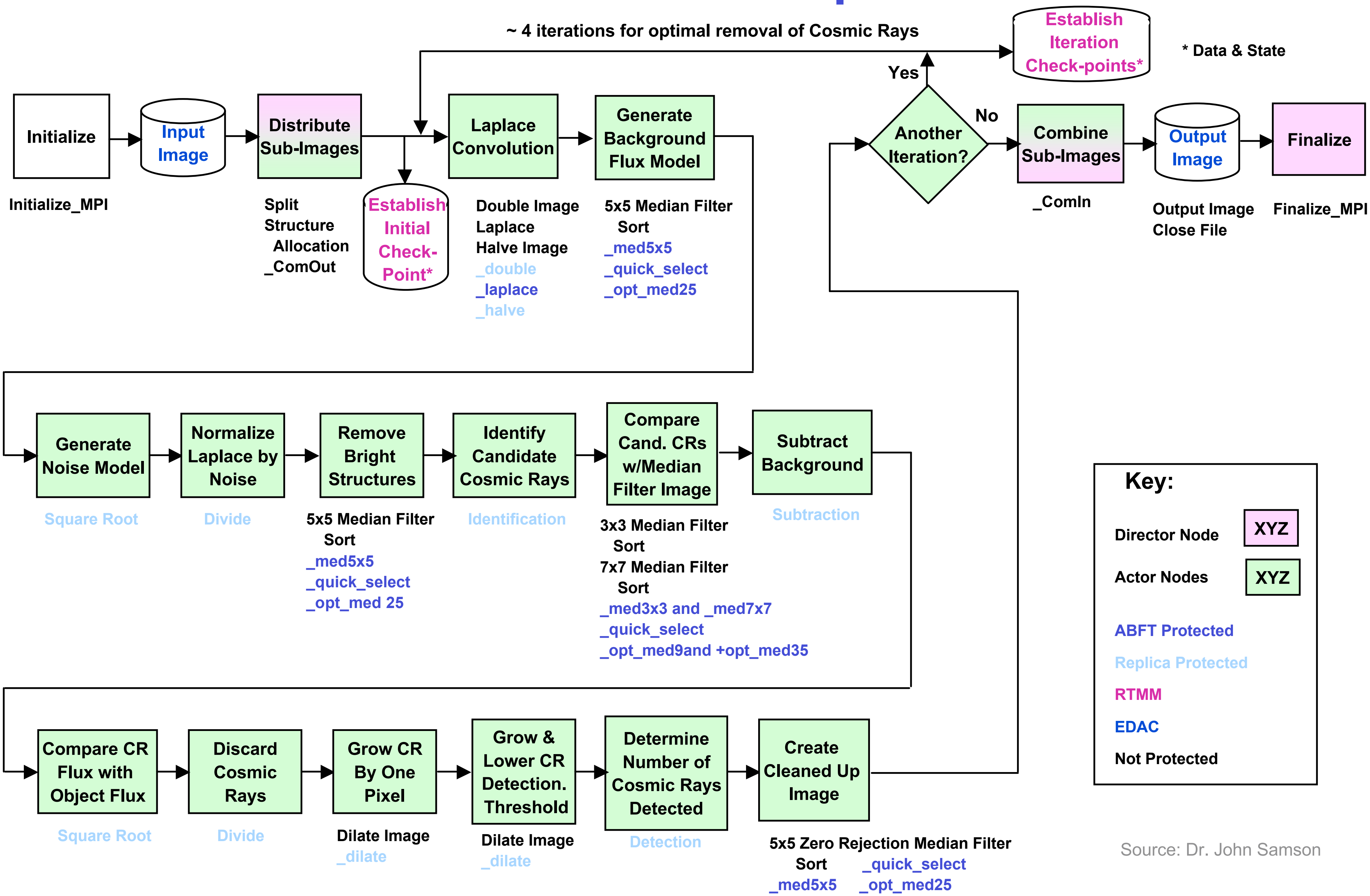
Source: Dr. John Samson

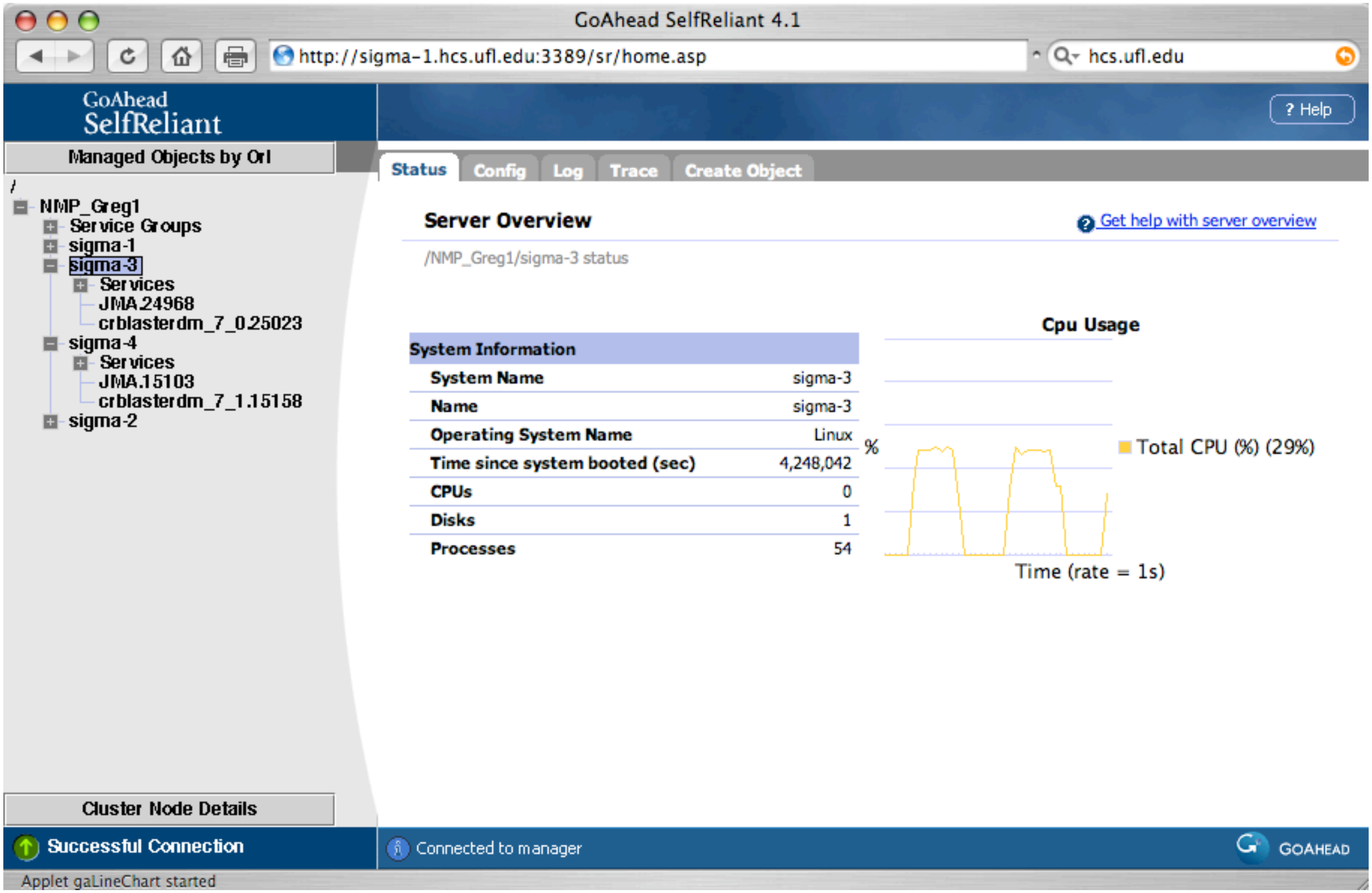
CRBLASTER Flow Diagram



Source: Dr. John Samson

CRBLASTER DM Implementation





DM is easy to use: *CRBLASTERDM*

"flies" on DM testbed – in just 3 hours!

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